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PENETRATION OF RENEWABLE POWER IN BANGLADESH

BY

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My research topic focused on the renewable transition in Bangladesh. Through my study, I have gained a deeper understanding of the challenges and opportunities in promoting sustainable energy in developing countries. I hope my findings will contribute to the ongoing efforts to address climate change and promote sustainable development.

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Once again, thank you for your guidance, support, and encouragement. I am proud to have been a student under your supervision and look forward to continuing our professional and academic relationship.

PENETRATION OF RENEWABLE POWER IN BANGLADESH

MUHAMMAD TALUT

ABSTRACT

Despite being a developing country in South Asia with a consistent ~7% GDP growth rate over the last two decades (2000-present), Bangladesh pledged to cut down its carbon emission to 10% by 2020 from electricity generation in its first Renewable Energy Policy enunciated in 2014. Later in 2020, it heightened its ambition to green the entire power sector by 2050. It decided on the progressive adoption of renewable technologies to tackle climate change and ensure energy security. This research addresses the central question of discerning the optimum policies and priority areas required to guide Bangladesh through its sustainable energy infrastructure transformation and to support it towards its aspiration of becoming a developed country by 2041. Following an extensive literature review, the study generated a conceptual framework for a vector autoregressive nonlinear logistic energy transition model for Bangladesh, conforming to several transition factors and variables such as past trends and future forecasts of energy demand, economic affordability, and other green transition factors pertinent to Bangladesh. As the first step, the primary assessment of the renewable potential (solar, wind, biomass, tidal etc.) in Bangladesh found it quite challenging to meet the future demand only through local green resources at the current efficiency level and transition rate. The seasonal variability, cooling load variance and future changes among appliances will also play a vital role in the power demand scenarios. The novel "sociotechnical capacity for green power transition" model incorporates the mapping and estimation of available resources, reviews of economic growth patterns and forecasts, advancement of technology and global market trends, cross-border power sharing, trade policies and other influencing variables. The model shows the capacity of the country to afford the maximum feasible amount of green energy at a particular time in the future based on the projections of the influential variables. Initially, the model considered seventeen variables that may contribute to the future green transition in Bangladesh, but nine variables were used following the concept of collinearity and correlation. A logistic vector autoregression model was coded in MATLAB based on the past ten years' trend (since renewable power in Bangladesh took off after 2010) and simulated to forecast future transition pathways. The simulation results indicate the effects and extent of the impact of various influencing factors on the green transition scenarios. Based on the findings, this work suggested how the renewable share in the energy mix should be progressively augmented according to factors like the future escalation in financial affordability, land availability or the technical advancement of the suitable renewable systems' overall efficiency for the country. The simulation results graphically indicate the prioritisation across the variables should be foreign aid> energy storage price> system efficiency>direct green power import>carbon taxation>per capita income>renewable power budget>land acquisition of large solar plant>renewable electricity price. It was then examined through the homologous findings from a survey and an interview to verify the reality nexus. The work concluded with formulating recommendations and illustrated ideas based on the findings intended to support policymakers and energy managers. The policy recommendations included prioritisation of bringing more foreign aid and support in, maximisation of use of industrial building rooftops and interconnecting household rooftop solar arrays to maximise aggregated power harvest saving agrarian lands, preferring applications like direct solar irrigation to opt out of expensive battery usage, facilitate direct solar charging station to recharge electric vehicles etc. It also forecasted the high times for adopting mass energy storage upon becoming viable for base load supply. In that nexus, the work demonstrated how the policy mix changes could accelerate Bangladesh's transition 5-8 times faster compared to the ‘current business as usual' path. The suggestions and ideas will help policymakers better understand the dynamic interrelations between different transition factors to decide over and plan the wide-scale adoption modes and implementation of renewable energy systems according to the accessible resources and fiscal potential of different regions in Bangladesh.

Contents

List of Figures

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    - Global Renewable Power Grid: Key Aspects and Challenges in Integration and Optimisation of Globally Interconnected Renewable Resources, A Master Dissertation for the fulfilment of MSc in Energy Policy at The University of Sussex, UK (Submitted in 5/9/2017), Originally authored by MUHAMMAD TALUT (author of this thesis), Supervised by Professor Steven Sorrell (https://profiles.sussex.ac.uk/p2497-steven-sorrell)

Signature: MUHAMMAD TALUT Date: 30/07/2023

1 Introduction

This study has focused on renewable power's penetration and the probable transition pathways in Bangladesh, a developing country in South Asia with a consistent economic growth since 2000 and a vision for becoming a developed state by 2041 and beyond. However, some challenges need addressing, especially concerning energy resources, policies and transforming the current dependency on fossil fuels to that of green energy. In addition, Bangladesh is highly vulnerable to the impacts of climate change, in particular sea-level rise, atmospheric heating, and flash flooding (IMF, 2019). Renewable energy technology is not only being considered indispensable to address the climate change but also it is becoming economically more feasible every year. At a considerably high pace it has already become a major source of energy worldwide. Bangladesh has also recognised these compulsions and benefits of adoption of this technology and the sensation has started to influence its national policies. The work identifies the key influencers with their extent of influence on green power transition in Bangladesh and assesses the prospective policymakers' acumen with the actionable policies to allow the transformation, but with links to low-carbon technologies and the policy drivers for these. To attain these objectives, it modelled the renewable transition capacity of Bangladesh and forecasted it sociotechnically.

Renewable resources are regarded as environmentally friendly, sustainable, and progressively cost-effective sources of energy. They can be distinguished from fossil fuels primarily based on their varied nature, widespread availability, and universal applicability. However, their most significant differentiating factor is in their capacity to generate neither greenhouse gases, which contribute to climate change, nor harmful emissions (IRENA, 2021). The costs of renewable energy resources are also seeing a downward trajectory at a sustainable pace, in contrast to the prevailing trend of increasing costs observed in fossil fuels, despite their current volatility (IEA, 2022).

The development of clean energy is of utmost importance in addressing the issue of climate change and mitigating its severe consequences. In 2022, global temperatures reached the fifth highest level on record, marking the eighth consecutive year of at least a 1^0 Celsius increase compared to pre-industrial levels. Simultaneously, a significant portion of the global population, approximately 745 million individuals, lack access to electricity (IEA, 2023). Furthermore, approximately 2.7 billion people, accounting for 38% of the population, rely on traditional biomass for household activities such as cooking, heating, and lighting, which poses significant health risks (GreenPeace, 2023).

The International Energy Agency (IEA) produces annual statistics that indicate an undeniable trend towards growth in clean energies. According to the IEA's forecasts, there will be a significant increase in the proportion of renewables in the global electricity supply, rising from 28.7% in 2021 to 43% in 2030 (IEA, 2022). Furthermore, renewables are expected to contribute two-thirds of the overall increase in electricity demand during this period, primarily driven by advancements in wind and photovoltaic technologies. Therefore, no country in the world can ignore its multifarious compulsive forces on their development trajectories.

Based on the analysis conducted by the International Energy Agency (IEA), it is projected that global electricity demand will see a substantial growth of 70% by the year 2040. Furthermore, the proportion of electricity consumption concerning final energy utilisation is anticipated to escalate from 18% to 24% within the same timeframe. This surge in demand can be mostly attributed to the rapid economic development of emerging nations such as India, China, Africa, the Middle East, and South-East Asia (IEA, 2019). Sensing the strong evidence, no country can ignore the undeniable appeal of the renewable energy technologies to meet this demand sustainably. Bangladesh realised it too (Alo, 2019).

In order to address its energy crisis, it is imperative for Bangladesh to place emphasis on the prioritisation of its shift towards renewable energy sources. Renewable energy sources have the potential to offer a sustainable and dependable solution by addressing issues such as overcapacity reduction, cost reduction in power generation, and mitigation of fuel shortages (IRENA, 2019). In order to attain energy security and environmentally sustainable objectives, Bangladesh must prioritise substantial financial expenditures, enhanced governance, and a steadfast policy commitment towards renewable energy (IRENA, 2019).

Bangladesh is widely regarded as one of the most densely populated countries with around 180 million people living on only 148,460 km² of land area. Being a Gangetic delta, it is mainly a plain land with a coastal belt at the south and a hilly tract at the east. It is the most riverine region on earth crisscrossed by thousands of rivers (NatGeo, 2019). Bangladesh's electricity consumption per capita, 608 kWh per annum, is still low compared to that of the developed regions (Power Division, 2023). As of October 2023, the total generation capacity is around 25 GW and 2.5 GW more to be added from recently erected nuclear plants. 90% of the electricity is generated from fossil-fuelled power plants to date (PGCB, 2023) and the rest is from cross-border import and a small number of renewable resources.

Some studies have already tried to delve into Bangladesh's renewable energy potential deeply and produced several quality documents. In a paper, Baky et al. concluded that being a tropical country situated on the tropic of cancer, the potential for solar energy and biomass is abundant in Bangladesh, and people have already started to harvest energy from these resources (Baky, et al., 2017). However, the per capita energy consumption is still low to be only 346 kgoe (Kilogram Oil Equivalent). In another study, Deb et al. estimated the solar energy potential of Bangladesh and found the daily sunlight hours in Bangladesh to range from 10 to 7 hours get further reduced by 54% or to around 4.6 hours to account for rainfall, cloud, and fog (Deb, et al., 2013). It also infers that with the increase in massive population and the subsequent power demand, it may not be possible for Bangladesh to produce adequate solar electricity with the current technology due to the scarcity of per capita land. Except for a few coastal locations, Bangladesh's wind prospects are not very convincing (Faijer & Arends, 2017). These inferences open the door to considering power importation from neighbouring countries like Bhutan, India, and China with sufficient potential for green energy (EnergyWorld, 2017). Despite these challenges, the country expressed honest interests about greening its power sector in recently (Alo, 2020; MoE, 2021; WB, 2020).

The country sensed the significance of the adoption of renewable systems to generate power in the recent past and aspired to produce 40% of total electricity from them by 2040 in 2018 (PSMP, 2018). However, recently it heightened its ambitions to become 100% carbon-free by 2050 (Prothom Alo, 2021).

It is clear that despite being a developing state with the limited economic capacity to afford any cost premium that may result from renewable systems, Bangladesh could not ignore sustainable energy technology due to its declining cost and rapid technological advancement. Therefore, according to rational predictions, the country realised the need for a progressive power plan to avoid the system transition shock that will eventually occur after two or three decades (Richter, 2018). Considering this issue, to the authors' knowledge, no systematic action or research has been undertaken by any authority to date in the Bangladesh context, highlighting the importance of undertaking this study for the sake of the country's sustainable future.

Transition Models are used for several purposes: i) to improve the understanding of the dynamics of existing systems, ii) to improve the performance of existing systems, iii) to predict the future state of existing systems, and iv) to design new operational strategies. A specialised system transition model is a simplified representation of (part of) the dynamic progression of a real-world system in change transition models programmed in computer software allow for simulation of the real-world dynamic systems captured in a simulation model: Simulation is "the activity of carrying out goal-directed experiments with a computer program" (Birta and Özmizrak, 1996). Robinson (2004) focuses on existing systems in his definition of simulation: "Experimentation with a simplified imitation (on a computer) of a system as it progresses through time, for better understanding and improving that system" (Robinson, 2004). Some transition models are generated for developed and rapidly developing countries available in the current knowledge pool. Still, they do not consider the context of the overpopulated developing state like Bangladesh, where energy demand is so high. Instead, they have emphasised cases like India, China, and Brazil contexts where the enormous potential for renewables exists but with a much lower population density than in Bangladesh. Resources are still scarce (Moll & Uiterkamp, 2006), but the impact is far more intense in Bangladesh.

Moreover, those studies did not converge their focus to optimising the transition considering factors like economic growth, affordability, or projected energy demand of a particular state. Massive system transitions like replacing GHG-emitting systems with green ones are impossible without extensive government intervention or national policy drives. Therefore, to model an optimised transitional propagation of green energy based on sociotechnical capacities is essential for many developing states to decide on the policy directives. In that context, Bangladesh needs it even more than most countries.

The study addresses the central question of how and what policies are needed to allow transformation to low-carbon options for the energy sector in Bangladesh. With the increasing installation and use of renewable energy (RE) resources, recent years have seen a thriving trend in the switch from thermal-dominant to renewable-dominant power systems (Davis et al., 2018, Gatto, 2022, Sun et al., 2022, Connolly et al., 2016). Although numerous factors may have contributed to this trend, adopting legally enforceable low-carbon energy policy support across several nations is the most responsible factor (Edmondson et al., 2019). This research addressed the need for plans, policies, and strategies for promoting renewable electricity in Bangladesh. It includes mapping of resources, a simulation of transition modelling based on economic growth forecast and future improvement in technical efficiency, appropriate technology and policy needs, country readiness and the required support policies to tackle such needed future transition whilst retaining the projected economic growth in line with becoming a developed country by 2041 and beyond.

1.1 Aim of the study

This study aims to demonstrate the impact of several sociotechnical variables on the renewable transition capacity of Bangladesh in nexus to capturing the dynamics of the transformation progression. It decided to mathematically model that capacity considering the available data for several sociotechnical variables assumed to influence the transition. Simulating the model by varying the variable trends, it will project different scenario to determine the extent of influence of those factors. Then it will assess the intentions and understanding of the stakeholders to augment the sociopolitical reality. It also intends to determine the optimum policies, plans and strategies for Bangladesh to enable the green transformation in the power sector to the maximum possible extent by 2041 and beyond. Here, the term 'optimum' denotes the best possible harmony in an array of technoeconomic, socioeconomic and environmental factors influencing the transition.

1.2 Objectives of the research

1. To predict the future power demand of Bangladesh through regression and extrapolation, taking into account population growth, economic development, seasonality from climate change and decarbonisation of transport and to determine the magnitude, aspects, and prospects of available renewable energy resources in Bangladesh through the mapping of the resources, namely solar, wind, tidal, biomass etc.
2. Incorporate green power transition capacity modelling to optimise the economic growth/purchasing power and price changes. Here the capacity denotes the amount of renewable power that can be generated and used by the country within its affordability endorsed by several influential sociotechnical parameters. The study will rationalise why such modelling is pertinent to capture the transition dynamics in a country like Bangladesh. It will consider the rise/change in affordability, the

efficiency of renewable technology and several other probable influential factors in future with time. Within this objective, the research will identify the main challenges and obstacles towards the target of nearly 100% renewable power in future and to determine how and at what optimal rate the renewable electricity the country could avail over time.

3. To explore the different policy options regarding the transformation, considering the existing systems in transition and to analyse each policy and their implications to an implementable renewable pathway for Bangladesh through comparative evaluation.
4. To determine and optimise the significant policy decisions from the government regarding future energy aspiration through exploratory analyses.
5. To determine the roles, responsibilities, and interests of the renewable pioneers and the neighbouring countries in the transition of Bangladesh, assessing the impact of effective climate/energy diplomacy to achieve the aid.

1.3 Intended Outcomes

• The study will produce an overview of the rationality of renewable transition in a developing country challenged with several endemic constraints.

• The research will introduce a scientific approach to model the energy transition capacity based on the driving factors for a developing country like Bangladesh. In this thesis, simulation models will be used to assess the performance of transition designs. Those assessments are intended to inspire recommendations for policy design, which will structurally improve Bangladesh's energy infrastructures whilst acknowledging their complexity. The model will tell what capacity the country will have at a certain period in the future

• It will provide a systemic understanding of the dynamics of renewable transition and the effects of various influential factors on it.

• It will generate skills for statistical/mathematical decision-making at policy levels for the researcher, which he can use in further policy formulation arenas.

• Analysing the practicability of such a transition will provide the decision-making directions to the policymakers in the energy sector.

• The same modelling technique and simulations can be improvised for other policy analyses and forecasts.

1.4 Thesis Algorithm

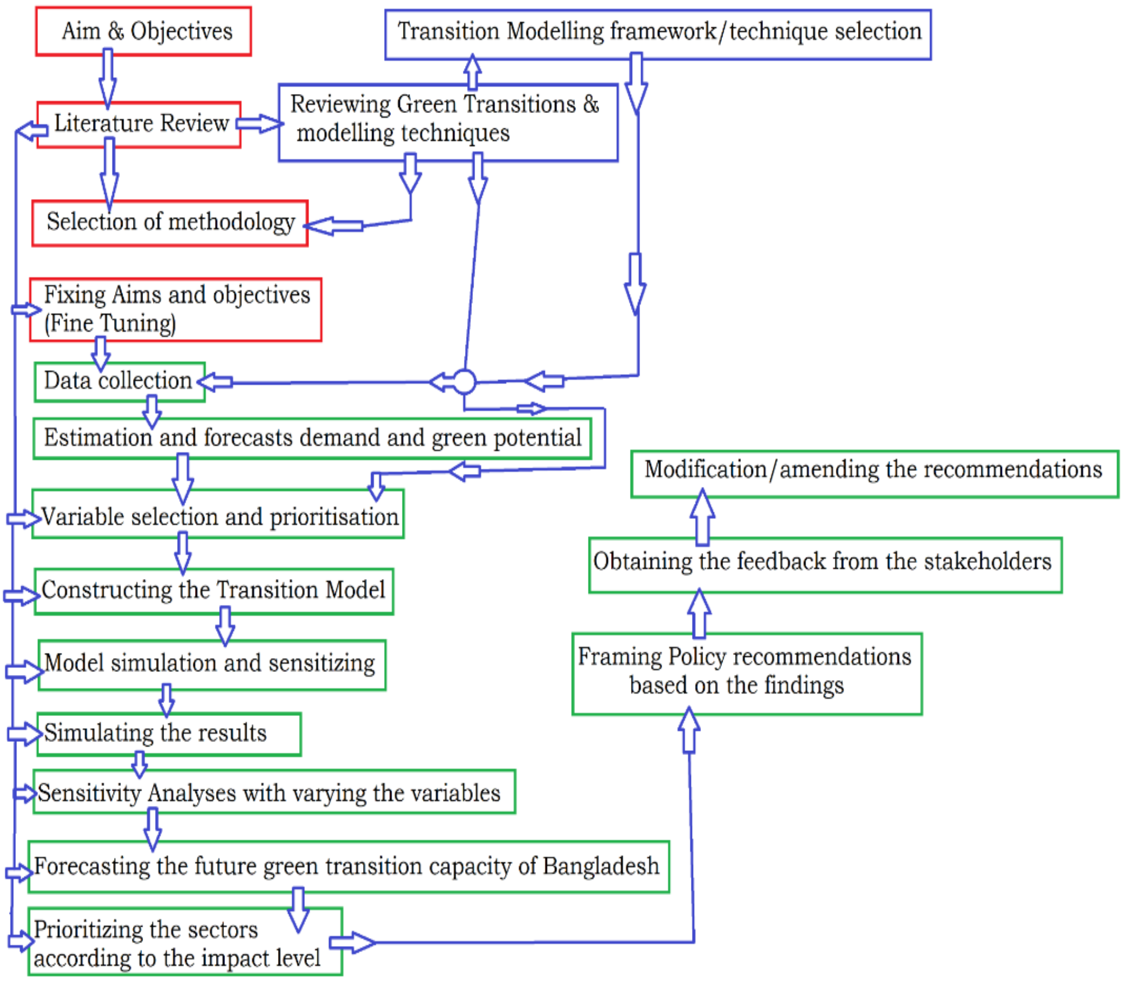

Figure 1 Thesis Progression Algorithm

(Red- Preliminary ideation, Blue- Literature review and method selection, Green- Implementation phases and outcome extractions)

Figure 1 shows the flow chart of the study's progress following the algorithmic steps. Figure 2 presents how the steps were inserted into several chapters. These elements can be largely divided into three groups. Blue shades indicate the background and Bangladeshi contexts, red denotes conceptual framework development, and green implies data collection, analyses and findings.

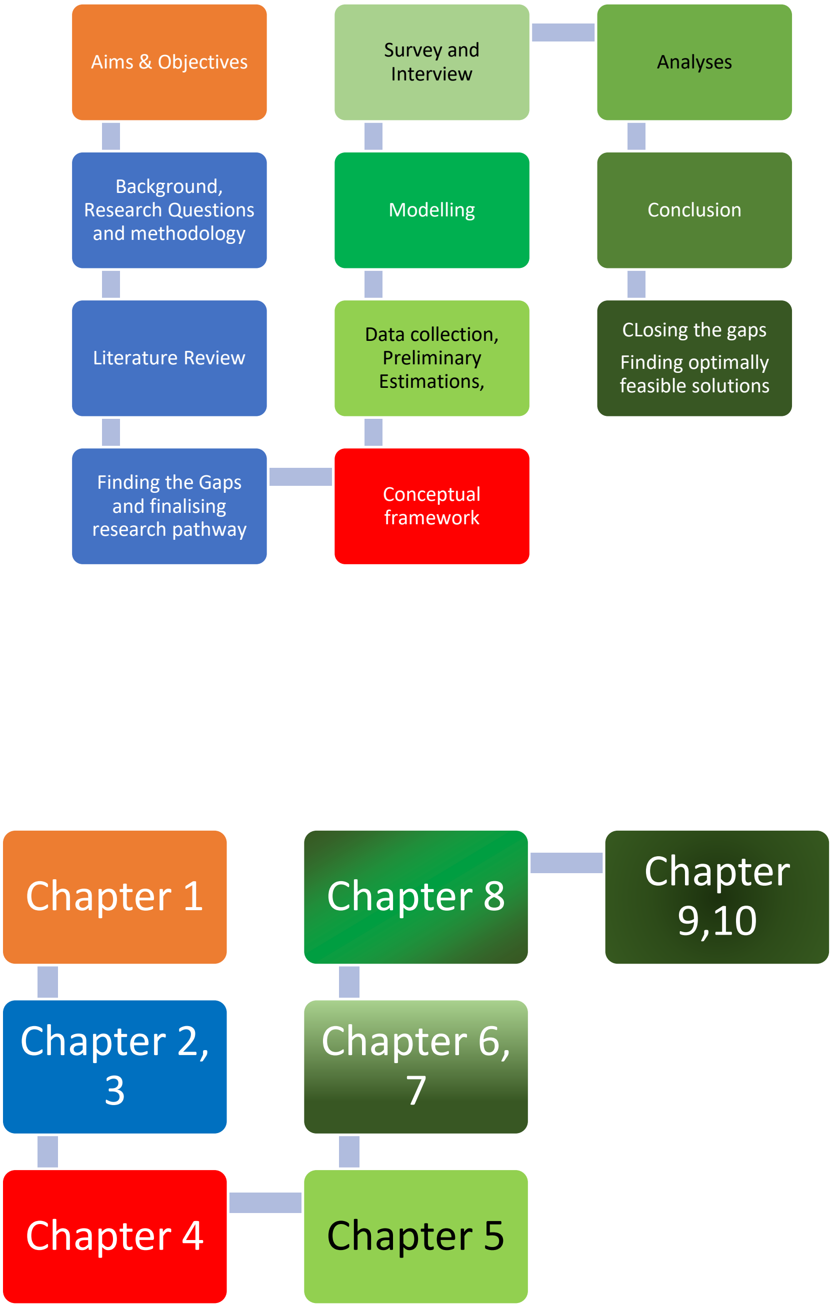

Figure 2 Thesis Composition Process

(Red and Orange- Preliminary ideation, Blue- Literature review and method selection, Greens- Implementation phases, data analysis, outcome extractions, appendices)

2 Background and Literature Review

Renewable energies garnered significant support from the global community via the Paris Accord, which was ratified during the World Climate Summit in December 2015, hosted in the city of Paris, France (UNDP, 2019). The pact, which came into effect in 2016, establishes a globally binding target for the first time in history.

Approximately 200 countries who have signed the agreement have committed to decreasing their emissions in order to ensure that the average global temperature by the conclusion of the present century remains "well below" 2 °C. This threshold represents the point beyond which climate change is anticipated to yield increasingly severe and detrimental consequences. The objective is to strive for a temperature increase of no more than 1.5 °C (IRENA, 2022). The use of renewable technology in the energy system is anticipated to yield significant economic benefits for both the global economy and development. Based on the findings of the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), it is imperative to increase the proportion of renewable energy in global electricity generation thrice by 2022, ultimately reaching a 90% share by 2030, to effectively achieve the objectives outlined in the Paris Agreement. To stimulate job creation and promote growth within the green economy, it is imperative to increase annual investments in renewable energy from the current amount of USD 1.3 trillion to USD 5 trillion (IRENA, 2022).

Several pieces of literature are already available in the existing knowledge pool regarding the renewable energy prospects and transition trends among rapidly developing countries like India(Bhat *et al.*, 2019), Brazil (Weng *et al.*, 2020), China and a few African countries. This section will incorporate a literature review of the past works pertinent to this study to produce a systemic review on the renewable energy transition modelling converging towards Green Power Transition modelling for Bangladesh. An elaborate review of the growth pattern of renewable energy among the third-world states is available from Qurayeshi and Hussain, coupled with environmental risk reduction and scaling up of Human Development Indices. Using the Kuznets Curve *(From a very simplistic viewpoint, this curve can suggest that economic growth is good for the environment)*, this report only addresses the risk scale in the form of ambient urban air pollution. It disregards the other scales, which may be more imperative (Hussain & Qurayeshi, 2005). This research wants to consider various factors, from natural hazards to catastrophic technical failure.

In 2009, two Chinese authors summarised the current trends and hitches in China's industrial development. They found that most of China's renewable energy technology is still transitional from research and development to industrial production. The industrial progress of sustainable energy systems still needs the formation of a wide array of technical trials and demonstration programs to analyse and investigate the resources, the conversion and market development experience, and then form complete sets of equipment design and manufacturing, cultivation and many other points (Wang & Li, 2009) The authors stressed the phase when China initiated its massive adoption and wide-scale implementation of energy transition policies. Despite being a bit archaic study (2009), the work presents substantial literature for this research, considering Bangladesh is entering a similar phase. At the same time, most of the renewable energy technology of Bangladesh is entirely free-rode and heavily imported from China.

Another extensive study was carried out by Moll et. al. where (Moll & Uiterkamp, 2006) some transition models were developed and discussed for rapidly developing countries. It concluded that the current energy models tend to be biased towards the experience from the existing energy systems and economies of industrialised countries, as experience from these systems has a long and successful tradition that leads to system inertia. Though this study mainly focused on the settings of rapidly developing countries, the inferences from it can be reasoned for the context of Bangladesh considering a few pertinent reflections as the transition would follow the BaU pathways among developing countries rather than adopted incentivised policies.

Alexander, James and Richardson established and ran another model in their study considering generation and demand challenges of a 100% renewable UK electricity grid and how that could be addressed with interconnection or energy storage (Alexander, et al., 2014). For their study, it was decided to consider two future demand scenarios to illustrate how demand can be met by renewable energy sources and the requirements needed to maintain the security of supply. Several variables were considered, and the dataset was collected to construct the conceptual framework. For example: To form the model, hourly or half-hourly data have been collected where possible for electricity demand and generation from renewable resources on the UK electricity network. This study introduced potential renewable energy mixes for the UK that met the proposed annual electricity demands set out in this study. The estimated capital costs for these scenarios ranged from £200 to £353 billion. However, when considering the hourly demand and generation profiles, the issue of generation variability becomes apparent because of the variable sources such as wind and solar PV. It was found that the level of available dispatchable generation in the UK (hydro, bioenergy and geothermal) in these scenarios is insufficient to meet demand when there is only a small contribution from wind because of high-pressure systems (anticyclones) across the whole of the UK. A range of technological solutions to balance the generation and demand of the UK electricity grid has been discussed. It was also determined that a mix of interconnection and energy storage technologies is required to ensure the future highly variable electricity grid is viable. In addition, consumer behaviour towards electricity usage will help reduce the amount of balancing required. However, one of the most important factors to the wide-scale renewable electricity grid's viability is the market structure and the governing energy policy. Furthermore, investment in key network upgrades and renewable capacity was found to be compulsory now to safeguard the future electricity grid. This study has many parallel and pertinent ingredients for this incumbent research on Bangladesh.

Energy infrastructures are the backbone of modern society and fundamental for many daily activities. For energy infrastructures (Ajah, 2009), environmental, economic, and social sustainability are vital and indispensable. Therefore, these issues must be addressed, such as climate change, scarcity and the depletion of resources, accessibility, affordability, reliability and quality of energy services, and security of energy supply. It is widely acknowledged that the energy infrastructure systems during the 21st century to deal with these issues are to be changed, for instance, through the massive introduction of renewable energy technologies and energy conservation. This research explores simulation models for ex-ante assessment of actions proposed to bring about structural change in Bangladesh's energy infrastructures and achieve a transition.

This multifaceted, low-carbon energy transition will fundamentally alter the geopolitics of energy in several ways, including changing power relations among and between power producers and consumers (Scholten & Bosman, 2016). Hydrocarbon-exporting countries face potentially negative economic and political impacts from reduced energy exports. In contrast, energy-importing countries can benefit from greater energy self-reliance and, in some cases, the export of clean energy technologies (Griffth, 2019). As such challenges and opportunities evolve, management of international relations via diplomacy will become an increasingly important mechanism of foreign policy as countries endeavour for strategic positioning in the future energy landscape. While various forms of multilateral diplomacy are necessary for concurrently aligning the energy transition interests of multiple stakeholders, bilateral diplomacy is the most direct means of pursuing national interests (Griffth, 2019). Along with the interrelated dynamics among the influential factors on the transition, the research demonstrated the strategic importance of fostering bilateral energy diplomacy with countries that can provide security of domestic energy supply, markets for the long-term monetisation of green resources and support for a shared economic dispersion as well. These strategic relations have energy at their core. These should extend to joint investment and science and technology collaboration to have maximum value for an emerging economy such as Bangladesh.

2.1 Significance and Motivation

Bangladesh's government also wants its personnel to have an insightful and thorough understanding of the issues they will be dealing with. It aids them with full support to attain that specific goal. In this era of specialisation, when the bureaucrats from developing countries are expected to be 'Jack of all trades but masters of at least one', being posted in the corresponding Ministry, the researcher has chosen the focus area of interest to be the 'Sustainable Energy'.

2.2 Country Profile: Bangladesh

Bangladesh, a country in South Asia, is the world's 8th-most populous country, with a population exceeding 162 million (CIA, 2023). Regarding area, it is the 92nd-largest country, spanning 147,570 square kilometres (56,980 sq mi). It shares land borders with India to the West and Myanmar to the East. It is also one of the most densely populated countries in the world, with 1,106 people per km^2 (CIA, 2023). Dhaka, its capital and largest city, is Bangladesh's economic, political, and cultural centre, followed by Chittagong, the country's largest seaport. Bangladesh constitutes the most extensive and eastern portion of the Bengal area, as stated by the Central Intelligence Agency (2023). The Bengal Delta, which holds the distinction of being the largest delta globally, exerts a significant influence on the geographical landscape of the country. The nation possesses a multitude of rivers and a substantial expanse of inland waterways, measuring around 8,046 kilometres (5,000 miles) (Atlas, 2019). The country is characterised by the presence of highland areas that are adorned with evergreen forests, primarily located in the Northeastern and Southeastern regions. The nation is also home to the world's longest stretch of coastline along the sea and boasts the greatest expanse of mangrove forest globally (CIA, 2023). The nation possesses a diverse array of flora and fauna, encompassing various plant species and wildlife, notably including the critically endangered Bengal tiger, which holds the distinction of being the country's national animal (CIA, 2023).

The modern nation of Bangladesh came into being as an autonomous state on December 16, 1971, following its secession from Pakistan and subsequent victory in the Bangladesh Liberation War. The territorial boundaries of the nation align with a significant chunk of the ancient and historically significant Bengal region in the eastern part of the Indian subcontinent. This territory has been inhabited for over four millennia, tracing its roots back to the Chalcolithic period (Birtannica, 2017). The historical development of the region is intricately connected with the historical narratives of Bengal and the wider Indian subcontinent (Britannica, 2017).

The political landscape of Bangladesh operates within the framework of a parliamentary representative democratic republic. In this system, the Prime Minister of Bangladesh serves as both the head of government and the leader of a multi-party system, with the executive power vested in the cabinet. The authority to create laws is entrusted to the government and parliament (Britannica, 2017). The Constitution of Bangladesh was drafted in the year 1972 and has since undergone sixteen modifications as of the present (EI, 2017). In 2016, the Economist Intelligence Unit classified Bangladesh as a "hybrid regime." Sheikh Hasina, the leader of the Bangladesh Awami League (AL), was successfully re-elected as the Prime Minister for an unprecedented fourth term in the 11th general election (EI, 2017). The cabinet members were sworn in on January 3, 2019. The government of the post-independence era encountered formidable problems. In the year 1975, the father of the individual in question was removed from power by the military, which subsequently led to a sequence of military coups. These coups ultimately culminated in the establishment of a government supported by the military, and subsequently, the formation of the Bangladesh Nationalist Party (BNP) in 1978. The aforementioned government also experienced a coup d'état in 1981, subsequently leading to a period of military-backed governance until the restoration of democratic elections in 1991. Since 1991, the Bangladesh Nationalist Party (BNP) and the Awami League (AL) have taken turns in governing, except for a temporary military-supported caretaker regime. This dictatorship, which was established to address democratic reform and combat corruption, postponed the scheduled parliamentary elections in January 2007 (CIA, 2023). The country achieved a complete transition to democratic governance in December 2008, as evidenced by the election of the Awami League (AL) and the appointment of Prime Minister Sheikh Hasina. The national election held in January 2014 resulted in a resounding victory for the incumbent AL party, as the BNP chose to boycott the election.

Consequently, this led to an extension of Prime Minister Hasina's tenure. In December 2018, Prime Minister Hasina successfully obtained a third straight term (fourth overall), when the Awami League alliance won 96% of the available seats. However, there were significant allegations of election fraud.

Nevertheless, the endorsement of the action mentioned above by the world community was obtained (CIA, 2023). Bangladesh has successfully decreased its poverty rate from over 50% to below 33%, attained the Millennium Development Goals pertaining to maternal and child health, and made notable advancements in the domain of food security with the aid of foreign development assistance subsequent to its independence. Since the year 2000, the economy has exhibited a consistent annual growth rate of approximately 6-7%. This sustained growth has led the country to attain the lower-middle income classification as determined by the World Bank in 2014 (CIA, 2023).

The economy of Bangladesh, which operates on a market-based system, has experienced rapid growth, positioning it among the fastest-growing economies globally. In terms of nominal value, it ranks as the 41st largest economy globally, while it holds the 30th position based on purchasing power parity. This economy is categorised as one of the emerging market middle-income nations known as the 'Next Eleven' and is also considered a Frontier market. Based on data provided by the International Monetary Fund (IMF), it can be observed that Bangladesh saw notable economic growth in 2016, positioning itself as the second fastest-growing large economy. This growth was quantified by a growth rate of 7.1%. According to the International Monetary Fund (IMF, 2019), Dhaka and Chittagong serve as the primary financial hubs of the country, housing the Dhaka Stock Exchange and the Chittagong Stock Exchange. In the year 2022, the per capita income attained a value of US$2,734 in nominal terms and $7,985 in terms of purchasing power parity. According to the Central Intelligence Agency (CIA, 2023), Bangladesh's financial sector is the second largest in the Indian subcontinent.

From 2004 to the present decade, Bangladesh has maintained an average GDP growth rate of 6.5%. This increase may be attributed mostly to the country's exports of readymade garments, the inflow of remittances, and the development of its domestic agriculture sector. The nation has implemented a strategy of export-oriented industrialization, focusing on important sectors such as textiles, shipbuilding, fish and shellfish, jute, and leather goods (Arun, 2019). Additionally, the country has made significant advancements in establishing self-reliant sectors such as medicines, steel production, and food processing. The telecommunication business in Bangladesh has experienced significant expansion, characterised by substantial investments from international corporations. Additionally, it is worth noting that Bangladesh possesses considerable deposits of natural gas, positioning it as the seventh-largest gas producer in the Asian region. There has been a notable rise in offshore exploration endeavours within the maritime jurisdiction of the Bay of Bengal. According to Banglapedia (2019), the region in question is also known for its significant reserves of limestone. The government endeavours to foster the advancement of the burgeoning information technology sector in the country through the implementation of the Digital Bangladesh initiatives (PC, 2020).

The nation of Bangladesh holds significant strategic importance for the economy of Northeast India, Nepal, and Bhutan. This is mostly due to the provision of maritime access through Bangladeshi seaports, which serve as crucial gateways for these landlocked regions and countries. China saw Bangladesh as a prospective access point for its geographically enclosed southwestern regions, encompassing Tibet, Sichuan, and Yunnan (CIA, 2023).

Bangladesh is a participant in various international organisations, including the D-8 Organisation for Economic Cooperation, the South Asian Association for Regional Cooperation, the International Monetary

Fund, the World Bank, the World Trade Organisation, and the Asian Infrastructure Investment Bank[1]. The economy is confronted with various challenges, including infrastructure bottlenecks, inadequate power and gas sources, instances of bureaucratic corruption, political instability, occurrences of natural calamities, and a shortage of trained labour. In 2017, Bangladesh's HDI (Human Development Index) was recorded at 0.608, placing the country within the medium human development category. This ranking positions Bangladesh at 136 out of a total of 189 countries and territories. From 1990 to 2017, there was a notable increase in Bangladesh's Human Development Index (HDI) value, rising from 0.387 to 0.608. This represents a substantial growth of 57.1 per cent over the specified period. From 1990 to 2017, there was a notable improvement in many indicators of human development in Bangladesh. Specifically, life expectancy at birth witnessed a significant rise of 14.4 years. Moreover, the mean years of schooling had an increase of 3.0 years, while the predicted years of schooling observed a growth of 5.8 years. According to the United Nations Development Programme (UNDP), in 2017, there was a significant growth of around 178.6 per cent in Bangladesh's Gross National Income (GNI) per capita from 1990 to 2017.

Despite recent progress, corruption in Bangladesh remains a persistent issue. According to all major ranking organisations, Bangladesh is consistently ranked among the most corrupt nations on the planet (BAP, 2015). According to Transparency International's 2017 Corruption Perception Index, the country ranks 143rd out of 180 nations (Transparency, 2018). The government's public sectors are regarded as the most corrupt in the country. Due to government control, the Anti-Corruption Commission, established in 2004, is mainly ineffective in investigating and preventing corruption (Zafarullah & Siddiquee, 2011).

Bangladesh has been constructing power plants and will continue to do so to meet the rising electricity demand. Some studies suggest a dearth of studies on the cost analysis of Bangladesh's fast-expanding energy sector due in part to insufficient data and a lack of government transparency (Yasmin, 2020). Firstly, a database of costs was created from several sources for this investigation. Public and private cost data from around the world were compared to estimate the cost of establishing power plants in Bangladesh. The results revealed an unusual characteristic of a fast-expanding economy (Sadovskaia *et al.*, 2019). Most public plants have greater capital costs than the global average (Zaman and Brudermann, 2018). Bangladesh has a large pricing disparity between the private and governmental sectors for equivalent power-producing technologies. In addition to the higher capital cost, the cost evolution indicated that constructing public power plants increases over time.

In contrast, the opposite is true in the private sector and globally. This study revealed a substantial association between corruption and the rising cost of power plants in the event of rising costs. Corruption may increase the price of a power plant in impoverished nations like Bangladesh. To mitigate the adverse effects of corruption on megaprojects, the government must develop a more transparent and supervised system for erecting power plants.

2.3 Bangladesh’s Energy Policy Today and Renewable Transition Momentum

Bangladesh suffers from an extensive energy crisis with the rapid and consistent expansion of the country's economic activities. The estimations and reserves of energy resources show potential, but a small fraction of them is being utilised, which proved insufficient and inefficient. Moreover, the impact of climate change and environmental pollution has also been significantly realised. As a result, successive governments have aimed to formulate an effective energy policy to address these concerns. The existing energy policies have also received extensive criticism, especially on energy export and extraction methods.

[1] https://thefinancialdaily.com/bangladesh-moving-to-developed-economy/

Bangladesh's Ministry of Power, Energy, and Mineral Resources formulated the country's first National Energy Policy (NEP) in 1996 to ensure proper exploration, production, and distribution. It also stressed the rational use of energy resources to sustainably meet the growing energy demands of different zones, consuming sectors, and consumer groups (Ahamad & Islam, 2011). In 2004 and 2008, the policy was revised in response to significant global and domestic changes. The revised policy included the following additional goals: to ensure environmentally sound, sustainable energy development programmes that cause minimal environmental damage; to encourage public and private sector participation in the development and management of the energy sector; and to electrify the entire nation by 2020. It met the target of expanding its primary grid across the nation.

Renewable energy progress in Bangladesh has lagged behind that of its South Asian neighbour India, which aims to install 275 GW of renewable capacity by 2027. In addition, Pakistan released a new renewable energy policy in 2019, expecting to significantly increase its ambition and target 30% renewable energy capacity by 2030, up from 5% currently (IEEFA, 2019).

In 2017, for the first time, renewable energy accounted for most of the new power capacity additions added in emerging markets. 2017 saw most of the world's new zero-carbon power capacity built in emerging markets (IRENA, 2018). The trend followed in 2018, during which renewables made up nearly two-thirds of all new power generation capacity added, led by emerging and developing nations. Momentum has moved firmly behind renewables and away from coal in developed and developing markets (IEEFA, 2019).

On the contrary, the excess fossil fuel power capacity planned for Bangladesh exposes the country to a high risk of stranded assets as renewable energy continues to become cheaper and more efficient than fossil fuel-based power going forward. However, despite its slow start, renewable energy in Bangladesh is now gaining momentum due to the ever-decreasing cost and improving the efficiency of renewable technology through the following steps:

- October 2018 saw Bangladesh’s first utility-scale solar plant (28 MW) commence operations. The exponent has already signed a Memorandum of Understanding (MoU) for constructing another solar plant of 100 MW (Islam, 2018).
- The following month, in November 2018, a unit of the Bangladesh Power Development Board (BPDB) issued an expression of interest for a 100 MW solar plant near Chittagong (Bellini, 2018).
- In addition, in November 2018, it was revealed that a U.S. National Renewable Energy Lab study had demonstrated significantly more wind power potential in Bangladesh than previously thought. Bangladesh Power Development Board has subsequently invited bidders for wind power projects around 150 MW (Parvez, 2018).
- In December 2018, the Bangladesh government approved proposals for five solar power projects totalling 227 MW (Islam, 2018).
- January 2019 saw the Asian Development Bank (ADB) approve funding for a 50 MW floating solar project on Kaptai Lake, with another being planned (Islam, 2019).
- In February 2019, a deal was announced to see U.A.E. invest in a 100 MW solar power plant in Bangladesh (IEEFA, 2019).
- In March 2019, the World Bank approved finance for 310 MW of Bangladeshi renewable energy projects starting with a 50 MW solar project in Feni (WorldBank, 2019).
- In addition, in March 2019, Saudi Arabian infrastructure company Alfanar signed an agreement with the Bangladesh Prime Minister to finance a 100 MW solar project built by the Electricity Generation Company of Bangladesh in the Feni district (Islam, 2019).
- In April 2019, Bangladesh’s second utility-scale plant was set to come online with a reported tariff of US$65/MWh. It compares to a estimated required tariff for the Rampal coal-fired power plant of US$99/MWh after tax, interest, and dredging subsidies (US$120/MWh without these subsidies) (IEEFA, 2019).

- In 2017, the implementation of the country's largest solar power project, 'Teesta Power Plant', started on 600 acres of abandoned bar land. Beximco Power Company Limited received work order worth 200 million US$. Eighty-five mounting piles have been installed in the solar power plant, and about 560,000 solar panels have been installed. It will be possible to generate 200 MW of electricity daily through 120 inverters from these solar panels. For this purpose, a 35.35 km long transmission line has been constructed from Teesta Power Plant to Rangpur to connect 28 transmission boxes, construct a 120 KVA transmission tower with substations and connect to the national grid. The plant was inaugurated in 2023.
- Sutiakhali Solar Power Plant is one of Bangladesh's largest solar power plants. Under the government's plan to generate solar power through renewable energy, the construction of a 50 MW solar power plant in Mymensingh began in 2017 and was completed in 2020. HDFC Sinpower Limited, a joint venture of Malaysia and Singapore under the management of the Bangladesh government, started working on implementing the project at the cost of about 80 million USD under the IPP (Independent Power Producer) method.
- All preparations have been completed to supply electricity to the national grid from one of the country's largest solar parks at Mongla from May 25, 2023. This park will supply 134.3 MW of peak electricity to the national grid. The plant is built on 350 acres of land by “Energy Renewables”, an industrial group Orion Group subsidiary. The most remarkable point is the plant was initially decided in 2014 as a coal-fired power project. Orion Group later scrapped the coal project and agreed with the Bangladesh Power Development Board (BPDB) in February 2019 to build the solar park.

2.4 Renewable Energy of Bangladesh in 2022

The Ministry of Power, Energy, and Mineral Resources announced its renewable policy guidelines in 2008, marking the beginning of Bangladesh's journey toward formulating and promulgating renewable energy policies. Since that time, up to 2022, Bangladesh has advanced gradually but steadily. In Bangladesh, the share of renewable energy sources like solar has increased recently. As a result, Bangladesh has 579 megawatts of installed renewable energy capacity (MW). Installations both on and off the grid are included. Solar PV accounts for 59.5 per cent, small-scale hydropower for 39.7 per cent, and biomass-biogas for 0.8 per cent (Viktor, 2022). Viktor also mentioned that over 65% of the energy used to generate electricity is still derived from fossil fuels like natural gas.

According to the 'National Solar Energy Roadmap 2021-41' prepared under the supervision of the Sustainable and Renewable Energy Development Authority (SREDA) and UNDP, Bangladesh can potentially generate 20,000 megawatts of green electricity by 2041 with a medium-scale strategy of solar electrification despite the scarcity of land (Faiz Ahmad Taiyeb, 2022). On the other hand, this capacity can reach 30,000 megawatts in a high-level solar model with 5 per cent of river basin development land, industrial rooftops, and other unused lands (Faiz Ahmad Taiyeb, 2022).

These recent developments and the prospect of cheaper renewable energy power imports from India allow Bangladesh to obtain far more than the targeted 10% of its electricity needs from renewables. With Bangladesh's rapidly growing electricity demand, renewable energy represents an increasingly cheap and quicker-to-build response that can enhance energy security and lessen the economic burden of diesel, coal and LNG imports (IEEFA, 2019).

The Sankey diagram of Bangladesh's Energy Balance shows the predominant dependence on native natural gas and traditional biomass for energy usage (Figure 3). It also presents poor industrial energy consumption (~11.01Mtoe) and a noticeable power loss (8.87Mtoe). A commanding portion of bio-waste energy use (7.92 Mtoe) denotes that the conventional mode of traditional firewood cooking across rural regions still prevails.

The previous two years have been exciting for the renewable energy industry as the uncertainty in the energy market caused by recent occurrences, such as the Russia-Ukraine war, has sped up the green transition. For instance, the annual capacity additions for solar photovoltaic power in 2021 totalled 175 GW, increasing the total solar PV capacity worldwide to 942 GW. This quick transition was driven by developing nations, with China taking the lead by adding the most solar power capacity each year. India and Brazil also made the top five (Browning Noah, n.d.).

The government made the praiseworthy decision to halt the construction of 10 coal power units planned to use imported coal in 2021. Social factors make it impractical to increase domestic coal extraction. According to the government's draft integrated energy and power master plan (IEPMP), coal plants now under construction may enhance coal's proportion of the energy mix in the short term, but coal's participation will gradually decline. Even with ultra-supercritical technology, coal remains a high-emission alternative that cannot be used as the primary energy source.

Recent occurrences over the past two years, whether they include LNG (Liquid Natural Gas) or imported coal, such as the local monetary devaluation against the US dollar and price swings on the global energy market, highlight the concerns of inflation and the debt burden that Bangladesh's heavily import-dependent energy mix poses. In 2021, Bangladesh gave energy industry subsidies totalling around US$7 billion, or about 6% of the nation's GDP (IEA, 2023). As a result, even though it had additional installed power generation capacity, it could not provide electricity because it could not afford the expensive fuel.

However, Bangladesh earned a name for itself among developing states in addressing climate change. Following the Paris Climate Change Agreement, the nation promised to boost its share of renewable energy. Additionally, in February 2023, the government passed the Mujib Climate Prosperity Plan, which commits to taking mitigating steps. Bangladesh could achieve its goal of sustainability by swiftly transitioning to renewable energy sources. Bangladesh requires ambitious objectives and clever tactics to shift to green power. The IEPMP asserts that clean energy is being promoted in Bangladesh and highlights the goal of utilising 40% clean energy by 2041. But concrete goals for achieving renewable energy sources are still obscure. The proposal mentioned ammonia or hydrogen as potential renewable energy sources, although these innovations are still nascent.

Bangladesh's solar and wind energy sources are promising. Solar modules on industrial rooftops and fallow land might provide more than 20,000 MW of solar power without affecting agricultural production. After years, Bangladesh is building wind energy projects. By the second part of this year, Cox's Bazar's 60 MW wind park will link to the grid, and Mongla's 55 MW wind park will begin construction. Bangladesh has begun an offshore wind energy feasibility assessment. If initial wind projects succeed, wind energy capacity could expand significantly.

Bangladesh's renewable energy sources have considerable spatiotemporal variability. Following the worldwide trend toward evidence-based analysis and smart, coordinated execution, the country must strongly commit to renewable energy. New, inexpensive technology is addressing renewables' drawbacks. Better storage technology, which deserves greater regulatory attention, could address worries about irradiance through a limited period. Optimum visions and strong political will can revolutionise the growth scenarios, emphasising the green energy sector.

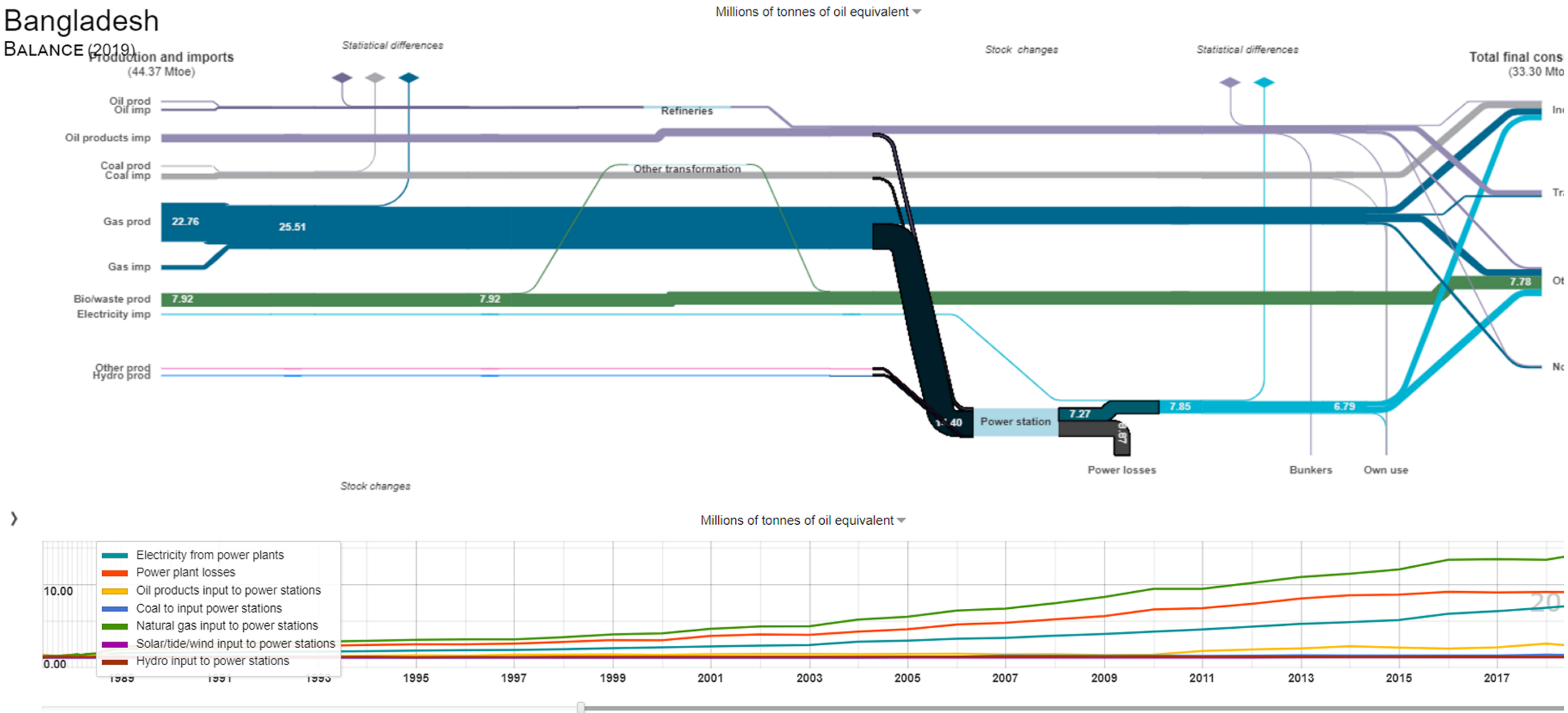

Figure 3: The Sankey Diagram of Bangladesh Energy Balance in all sectors for 2019 (IEA, 2022)

2.5 Organisations, Agencies and Tariffs

2.5.1 Power Division of Bangladesh

In Bangladesh, the Power Division of the Ministry of Electricity, Energy, and Mineral Resources is responsible for all power generating, transmission, and distribution-related activities. It oversees all issues and policies in the Electricity industry. In addition, it extends, rehabilitates, and modernises electricity generation, transmission, and distribution services following the rising national demand and formulates corresponding action plans and programs. It supports private and joint venture participation in addition to government investment in the electricity sector. Armed with a vast array of bureaucrats, technocrats, engineers, policy experts, and other employees, the division seeks to enhance the standard of living of rural people through rural electrification and the adoption of renewable energy in those locations. It is responsible for overseeing the revenue and commercial activities of utilities. In addition, it is responsible for promoting renewable energy and energy efficiency through the formation of policy, legislation, rules, regulations, various incentive systems, and power-related research and development (PD, 2019). The researcher is currently employed as a policymaking associate in the Power Division.

2.5.2 Bangladesh Energy Regulatory Commission

The commission is required by law to regulate the prices, tariffs, and usage of electricity, gas, and petroleum goods throughout Bangladesh (BERC, 2019). It was founded on March 13, 2003, by a legislative Act of the Bangladeshi government. The Commission became operational on April 27, 2004, when two of the five members, including the chairperson, were appointed.

2.5.3 Sustainable & Renewable Energy Development Authority

The Government of the People's Republic of Bangladesh enacted "The Sustainable and Renewable Energy Development Authority" (SREDA) Act 2012 to reduce global warming and environmental hazard risks and ensure energy security by reducing reliance on fossil fuels and expanding renewable energy usage. The Authority also seeks to avoid energy waste in the domestic, commercial, and industrial sectors by promoting energy efficiency and conservation. The following five wings carry out SREDA's activities:

1. Administration Wing
2. Renewable Energy Wing
3. Energy Efficiency & Conservation Wing
4. Finance Wing
5. Policy & Research Wing

2.5.4 Bangladesh Power and Energy Research Council

Bangladesh Energy and Power Research Council (EPRC) was established to respond to these difficulties by assuring new affordable, sustainable energy supplies to fuel Bangladesh's rapidly expanding economy. In light of this, the Bangladesh Energy and Power Research Council (BEPRC) commenced operations following the enactment of the "Bangladesh Energy and Power Research Research Council Act, 2015" to promote technological innovation in the energy and power sector and ensure energy security through research and development. It is the first innovation-encouraging institute in the power and energy arena established by the government. It has the following goals:

- To create an international online clearinghouse to highlight research requirements in the nation's energy and power sector and to encourage innovative solutions to satisfy these demands.
- To develop and solidify domestic research capacities to meet the nation's energy and power infrastructure requirements.
- To enhance administrative and financial infrastructure in support of research.

- To finance, coordinate, and manage grants and scholarships for research.
- To develop client-focused and demand-driven technology and disseminate research results.

2.5.5 Power Tariffs

The power tariff in Bangladesh is regulated by Bangladesh Energy Regulatory Commission and adjusted depending on different capacity distribution lines. Consumers who obtain connections from high-capacity distribution lines must pay higher bills than those from low-capacity lines (EnergyBangla, 2022). The latest retail rate for household consumers using 0-50 kWh is at USc 4.5 per kWh; 0-75 kWh at USc 5.5 per kWh; 76-200 kWh at USc 6.45 per kWh; 201-300 kWh at USc 6.70 per kWh; 301-400 kWh at USc 7.02 per kWh; 401-600 units at USc 10.30 per kWh and above 600 units at USc 12.72 per kWh. All the customers will have to pay USc 25 as a demand charge for those who initiated their lines from 230V distribution lines per day. Consumers that fall between the load capacities of 50 kW to 5 MW of power have to pay around 8 USc per kWh of electricity (EnergyBangla, 2022). The tariff in the peak hours (5 pm to 11 pm) is USc 10 and USc 7.20 in off-peak hours (11 pm to 5 pm). Most middle-class people have this connection category in their households (EnergyBangla, 2022).

[1 US$≈114.50 Bangladeshi Taka (Tk) on 12/09/2022, End of day prices provided by Morningstar. Corporate Actions data provided by Thomson Reuters, Source: Online]

Table 1 Tariff rates of Electricity in Bangladesh (BPDB, 2022)[2]

SL		Customer Category and Slab	Tariff Per kWh Rate (USDcents) Effective from Bill month September 2022	Service Charge* (USDcents/Month)	Demand Charge* (USDcents/kWh/Month)
1		Category A: Residential			
		Lifeline: 1-50 Units	4.50	1-Phase: 15.00 3-Phase: 40.00	20.00
	a	First Step: From 00 to 75 units	5.50		
	b	Second Step: From 76 to 200 units	6.14		
	c	Third Step: From 201 to 300 units	6.36		
	d	Fourth Step: From 301 to 400 units	6.63		
	e	Fifth Step: From 401 to 600 units	9.70		
	f	Sixth Step: From 601 to above	10.98		
2		Category B: Agricultural pumping	4.82	40.00	50.00 (Applicable for approved demand more than 30 kWh)
3		Category C: Small Industries			
	a	Flat Rate	8.66	80.00	50.00 (Applicable for approved demand more than 30 kWh)
	b	Off-Peak Time	7.90		
	c	Peak Time	10.24		
4		Category D: Non-Residential (Light & Power)	6.22	1-Phase: 15.00 3-Phase: 40.00	25.00
5		Category E: Commercial & Office			
	a	Flat Rate	10.80	1-Phase: 15.00 3-Phase: 40.00	30.00
	b	Off-Peak Time	9.45		
	c	Peak Time	13.98		
6		Category F: Medium Voltage, General Purpose (11 KV)			
	a	Flat Rate	8.57	450.00	55.00 (For Maximum Demand)
	b	Off-Peak Time	7.88		
	c	Peak Time	10.57		
7		Category G-2: Extra High Voltage, General Purpose (132 KV)			
	a	Flat Rate	8.35	500.00	40.00 (For Maximum Demand)
	b	Off-Peak Time	7.74		
	c	Peak Time	10.47		
8		Category H: High Voltage, General Purpose (33 KV)			
	a	Flat Rate	8.49	450.00	40.00 (For Maximum Demand)
	b	Off-Peak Time	7.82		
	c	Peak Time	10.52		
9		Category J: Street Light and Water Pumps	8.17	210.00	40.00

[1 US$~114.50=Bangladeshi Taka on 12/09/2022, End of day prices provided by Morningstar. Corporate Actions data provided by Thomson Reuters, Source: Online]

International agencies like the World Bank and JICA suggest that Bangladesh should raise the tariff of domestic electricity (Power Division, 2016). To cover the total supply cost, BPDB should reduce subsidies and simultaneously elevate the electricity bulk rate ceilings and corresponding tariffs. The electricity tariff table is categorised by consumption volume. To date, a reduced rate is set for households with a low income. However, when Bangladesh can increase its electricity generation, low-income households should be given

[2] [Conversion was done with the currency exchange rate of 1 US$~114.50 Bangladeshi Taka on 12/09/2022, End of day prices provided by Morningstar. Corporate Actions data provided by Thomson Reuters, Source: Online]

special consideration. The policy for such imposition may be relaxed because of concerns about the affordability of low-income households.

2.6 Renewable Resources in Bangladesh

The assessment of renewable resources in a country is essential to determine its capacity to meet the demand from such sources natively. Most of the countries are not self-sufficient in their energy requirements in today's fossil-fuelled civilisation (Jhonson, 2013). They have to import fuel from the fuel surplus countries. The following sections will assess the renewable sources and their potential along with the plausibility to meet the electricity demand of Bangladesh. This section is crucial to decide over the green power import from neighbouring states. In that case, green power import would become an influential variable in the transition model. The section also discusses the technoeconomic feasibility of each option.

2.6.1 Solar

The major harvestable sources of renewables are solar, wind and biomass in Bangladesh to date. Owing to its tropical geolocation, it enjoys bountiful high-intensity insolation throughout the year across the entire state except for a monsoon eclipse (Rahman, 2016). Hydroelectricity has a stagnant capacity of 250 MW (peak) saturated already (BPDB, 2023).

Bangladesh is a South Asian country located between latitudes 20°34' and 26°39' north and longitudes 80°00' and 90°41' east. Therefore, it is an ideal location for solar energy utilisation. Also, as a subtropical country, sunlight is plentiful 70% of the year. This makes using photovoltaic panels effective in Bangladesh, where average daily solar radiation is 4-6.5 kWh/m^2 and maximum radiation is generally received in March-April and minimum in December-January (Chowdhury, 2015). A solar panel efficiency of 20% with a $1m^2$ surface area would produce 364 kWh of power per year. With a payback period of 6.08 years, solar energy can be a viable solution for the green power supply in Bangladesh (Rahman, et al., 2015).

Quantification of the benefits of a solar panel is a decisive step in the economic feasibility assessment of solar panel activities. A study was done by Rahman et. al., to determine the NPV, BCR and IRR of the solar panel, the cost of solar panels, the benefits of solar panels and then the economic viability of solar electricity production from solar panels was estimated. The data show that the average initial investment or cash outflow for solar home systems (battery plus module) use in Bangladesh is US$ 260.55 (Rahman, et al., 2015). Annual operation and maintenance (O&M) costs of ingredients were related to repair and maintenance. It was also found that the average operation and maintenance cost was US$ 1.02 and increased based on an 8% inflation rate for the solar panel lifetime of 14 years (Rahman, et al., 2015).

Figure 4 Average monthly temperatures and weather, sunny and cloudy days in Bangladesh (HickersBay, 2023)

The benefits of establishing and operating a solar panel fall into two essential categories: monetary and environmental. The monetary benefits are the saved costs of energy substituted by electrical energy produced. To evaluate the advantages, an indirect method is used. Placing market values in terms of alternative electricity for a certain end use is the most practical approach (Rahman, et al., 2015). It was estimated from the data that the average cash inflow was US$ 43.57, and the average salvage value was US$ 12.35 in the Bogra district, with an average cash inflow was US$ 37.70. The salvage value was US$ 15 in the Mymensingh district. The NPV, BCR and IRR were calculated on discount rates of 10% and 12 % for the Bogra district and 8% and 10% for the Mymensingh district. Discount rates were used to get positive NPV and negative NPV values. At a discount rate of 10%, NPV was US$ 3.12 and BCR was 1.0; at a discount rate of 12%, NPV was US$21.21 in the Bogra district; those values were US$ 10.51, 1.04, US$ 18.77, respectively, in Mymensingh district. Using both discounting rates (Lower discounting rate 10% and upper discounting rate 12%). The IRR of 10.26% was greater than the opportunity cost of capital (8% lending interest rate), and the project was economically viable in Bogra district (Rahman, et al., 2015). In the case of Mymensingh district, using both discounting rates (Lower discounting rate 8% and upper discounting rate 10%), it was found that the IRR 8.72%, which was greater than the opportunity, cost of capital (8%, lending rate of interest). The paper also calculated the payback period for both districts, which was 6.08 years for Bogra and 7.06 years for the Mymensingh district. The project's payback period was less than the average solar panel lifetime (15 years). Therefore, the project was economically viable and acceptable (Rahman, et al., 2015). The same study claimed that among solar, wind, hydro and biomass, technoeconomically solar PV is the most feasible renewable system for Bangladesh so far.

The area of solar panels required per person to supply all necessary energy is estimated. Developed nations such as Australia and Singapore typically consume approximately 10 MWh of power per person yearly (Andrew Blakers and Ricardo Rüther, 2023). It must double to accommodate transportation, cooling, and industrial electrification by the next decade. Assuming 22% efficient panels and a 17% DC capacity factor (averaged across rooftop solar and solar farms), 13 kW per individual occupying 60 m^2 of space was found.

Suppose we consider this estimation and assume Bangladesh will become a developed country by 2041. In that case, the major constraint against solar harvest in Bangladesh will be limited land area due to the high density of the population. Fortunately, there are some significant portions of land where population density is much lower than the urban regions and where arable lands are rare. These land masses can be used for generating solar power. Recently a 20MW solar power plant was erected at Teknaf, a South-eastern sub-district of Bangladesh covering 116 acres of land, which denotes it takes on an average, practically, 5.8 acres of land to install 1MW solar panels in Bangladesh (EnergyBangla, 2018). Conversely, Bangladesh enjoys substantial volumes of solar radiation with 1,900 kWh/m^2 per year, daily, which equals to 4 to 4.5 kWh/m^2. On average, a 1-MW solar power facility can generate 4,000 kWh per day. Consequently, it produces 1,200,000 units per month and 14,400,000 units (0.0144 TWh) annually. This 0.0144 TWh power will come from 5 acre of land. Therefore, it would require 138,888 acres of land to generate 400 TWh (the projected demand by the year 2040) of electricity. In the case of a small agronomic country with a highly dense population (arable land 60%) like Bangladesh, where the total land area is only 147,570 km^2, such a big portion of solarable land is rarely available in one congregated piece. However, considering the future improvement in the efficiency of solar panels, the solar power share in the energy mix may be elevated at a commensurate pace.

The Chittagong hill tracts and the Northeastern *Haor*[3] region of Bangladesh, comprising an area of 13,184+4,450 km^2 have relatively much less population density than other flat arable regions. These sections can be considered for the massive green power generation through hilly terrain is generally found to be challenging to install large solar plants. The policymakers contemplate that installing floating solar projects on the lakes and infertile sedimented river bars might suit Bangladesh as it faces land scarcity problems for implementing large solar schemes (Hossain, 2019). However, the ecosystem of those regions may face vulnerability issues that need further discretionary research.

2.6.2 Wind

The rampant acceleration of wind power has become substantially influential in the renewable transition worldwide. Despite increased rotor diameters, hub heights, and nameplate capacity, turbine prices have decreased significantly during the past decade. In 2019, price disparities between turbines with varying rotor diameters shrank dramatically. It is evidenced by the small price difference between turbines with rotor diameters greater than 100 meters and those with rotor diameters less than 100 meters (IRNEA, 2022).

[3] A haor is a wetland ecosystem in the north-eastern part of Bangladesh which physically is a bowl or saucer shaped shallow depression, also known as a backswamp.

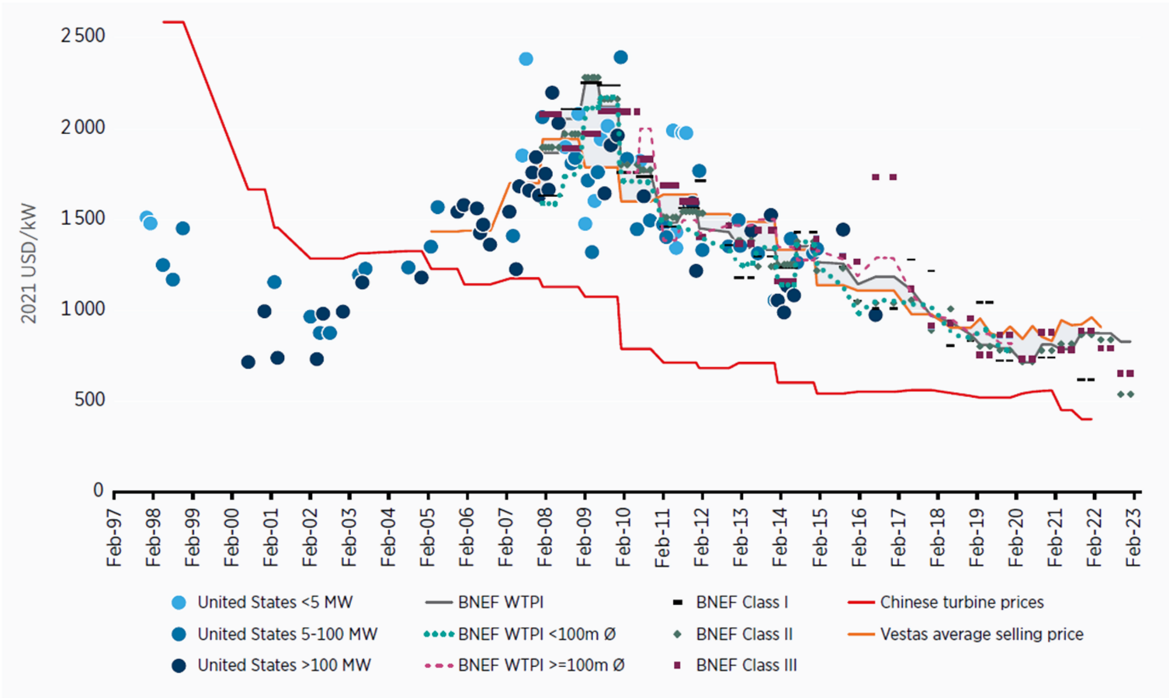

Figure 5 Worldwide wind turbine price indices and price trends, 1997-2021 (IRENA, 2022)

However, the wind prospect scenario is not much convincing as solar in Bangladesh as it is a flat country bordered by mountainous lines along the East and the North rims. Nonetheless, the south of this country is a highly irregular deltaic coastline of about 580-kilometre length. The latest wind mapping jointly done by NREL and USAID in Bangladesh obtained the following results.

Table 2 Bangladesh wind mapping results (USAID-NREL, 2018)

Wind Speed Range (m/s)	Square Kilometres (Km²)	Acres of Land	Estimated MW (Based on 0.6 Km²/MW)
0-4.75	14,769	3,647,943	24,320
4.75-5.25	51,966	12,835,602	85,571
5.25-5.75	37,328	9,318,816	62,125
5.75-6.25	12,276	3,032,172	20,214
6.25-6.75	6039	1,504,971	10,033
6.75-7.25	2,196	542,412	3,616
7.25-7.75	162	40,014	267

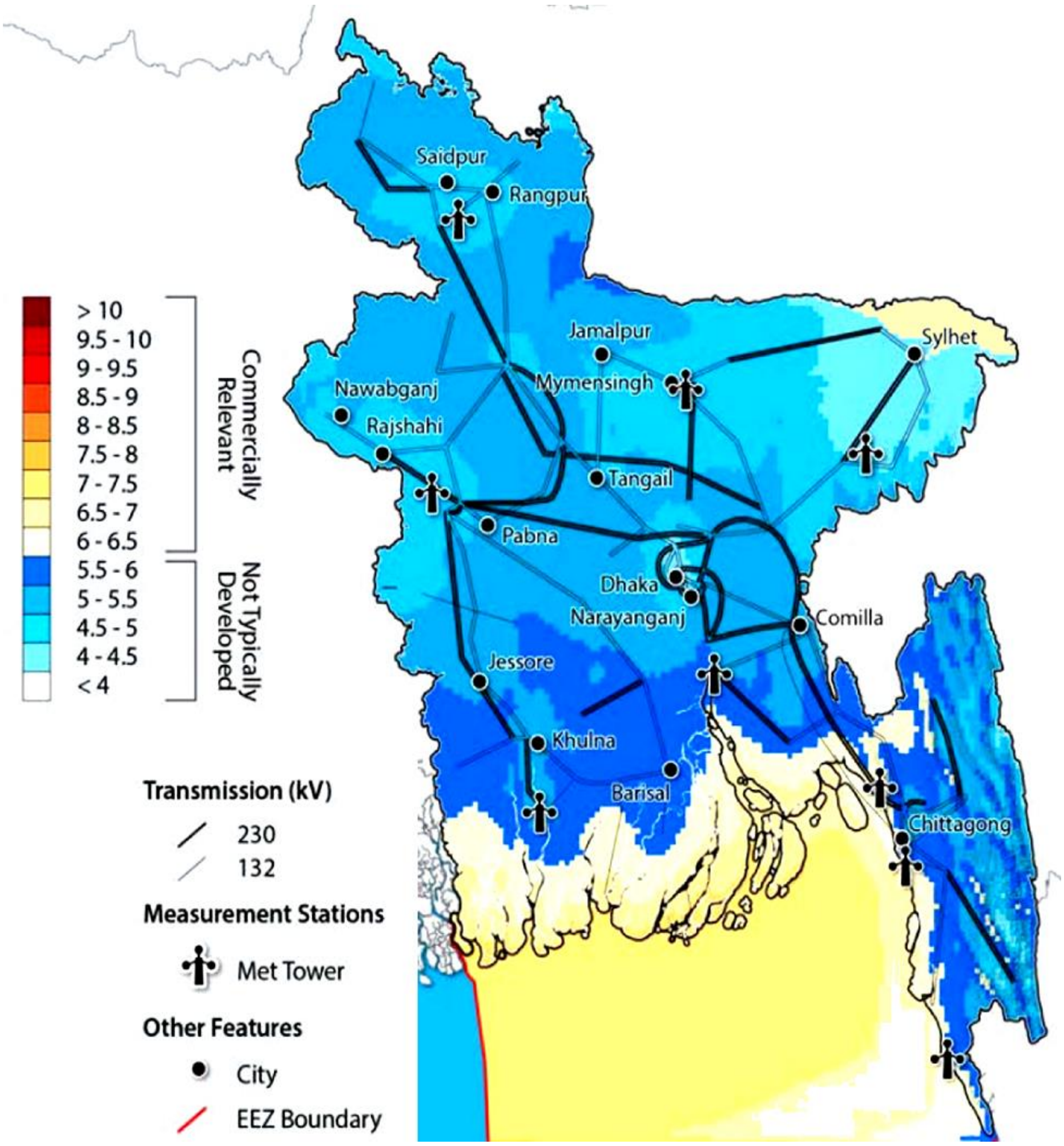

Figure 6 Wind Energy Potential in Bangladesh (USAID-NREL, 2018)

The results denote that, for wind speeds of 5.75–7.75 m/s, there is more than 20,000 km^2 of land with a gross wind potential of over **30,000 MW** (USAID-NREL, 2018). Although this estimate is not pragmatic when proper filters are applied to screen out undesirable land for wind development, it suggests that Bangladesh's 10% renewable target by 2021 is achievable (USAID-NREL, 2018). Nevertheless, there are harsh hurdles to elevating the wind share beyond that target due to various technoeconomic obstacles.

Suppose low wind speed-optimised turbines like VESTAS110-2MW are installed in a single row along the coastline where the average wind speed is highest, at every half kilometre (580X2=1160). If another row is installed, it will double the power. In that case, an approximate 2.3 GW capacity can be yielded with an aggregated annual generation of only 12 TWh.

Thus, to meet the entire power demand in 2041, the 2MW turbines needed is more than 100,000, considerably higher than the land available for such purposes in Bangladesh.

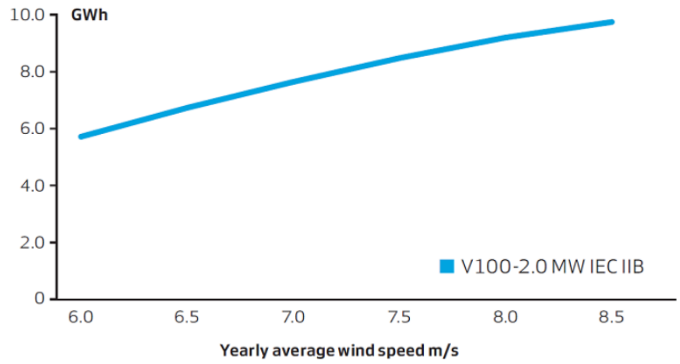

Figure 7 Yearly Performance curve of VESTAS100 2MW Wind Turbines (Vestas, 2019)

Offshore wind turbines could be a viable option for producing more consistent wind power but at a much higher installation and maintenance cost, up to 4/5 times (Sohag *et al.*, 2020). It is not an affordable choice for the current developing economy. More extensive research is needed for significant policy and business decisions. Frequent cyclones arising from the Indian Ocean are another massive challenge that may increase the budget for such a venture. During the summer and monsoon seasons (March to October), very low-pressure areas and storm wind speeds of 200 to 300 km/h can be probable. Wind turbines must be strong enough to withstand these high wind speeds. However, wind can still be used in the energy mix to the optimum extent to endorse the sustainable power transition on techno-economic viability (Haque, 2018).

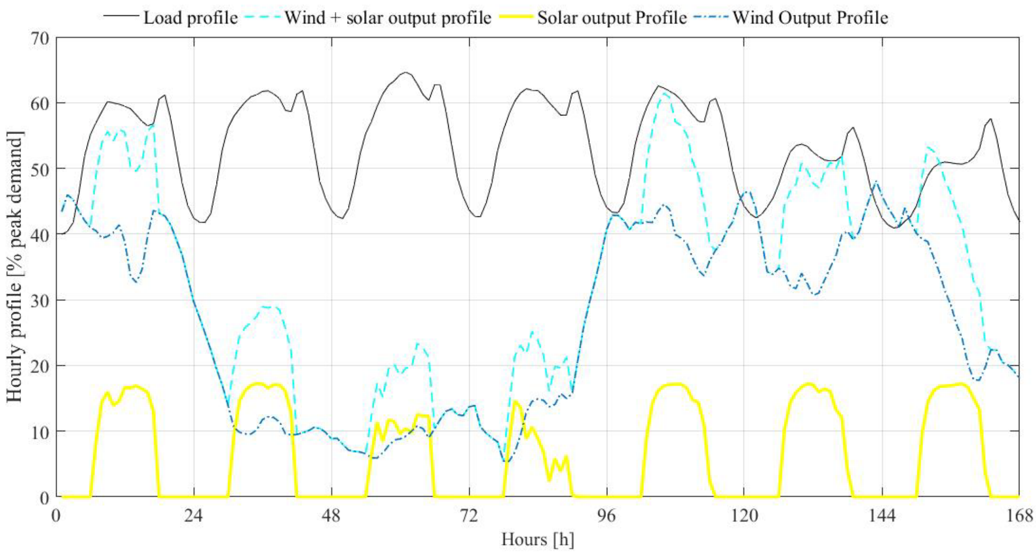

Figure 8: An example of Simulated hourly profiles of wind, solar, wind–-solar hybrid system output confirming a base-load supply (GW, Location California, USA) (Child *et al.*, 2019)

The highly erratic nature of both solar and wind power availability in Bangladesh mandates the demand for additional storage systems to ensure consistent flow to the grid and user ends. Hybridising multiple resources and interconnection from dispersed locations can considerably smoothen power supply variability from renewable systems (Figure 8). Bangladesh can use the technique to smoothen its aggregation and maximise the generation to fulfil its renewable targets (Mannan et al., 2015). Since battery technology is already improving faster regarding cost and efficiency, it should be seriously considered for mass-scale use for integrated transformation.

2.6.3 Biomass

Because of its large population, Bangladesh has substantial potential for biomass gasification-based electricity. Renewable energy in the form of traditional biomass is one of the main sources of primary energy in the country, comprising some 35-60% per cent of total primary energy uses; common biomass resources available in the country are rice husk, crop residue, wood, jute stick, animal waste, municipal waste, sugarcane bagasse etc. Nonetheless, the government is discouraging power generation from vegetable waste due to overharvesting and fertility degradation. It instead encourages returning them to the croplands in rotational crop technique (M Nasim, 2017). This technology can be disseminated on a larger scale for electricity generation. Biogas, mainly from animal and municipal wastes, may be one of the promising renewable energy resources for Bangladesh. There are 44,000 household-based and village-level biogas plants nationwide (T. Chowdhury *et al.*, 2020). It is a potential source to harness basic biogas technology for cooking and rural and peri-urban electrification to provide electricity during power shortfalls. $8.6X10^6$ m^3 of combustible biogas can be derived from the decomposed biomasses suitable for generating power by gas-driven generators (SREDA, 2019). This gas could produce 5 GW of power driving IC engines or turbines. If human faeces can be added to the generation scheme, the production may be brought into a significant amount of 21 TWh of cleaner energy.

Human faecal waste generation (in lower-middle income countries) is around 0.25 Kg/Capita/Day. At present, 164.7 million people may produce 41,175,000 Kg of faecal waste. In general, 1 kg of human waste produces 0.7 litres of biogas. In that case, the annual biogas production from 164.7 million people will be $1.05X10^7$ m^3 (since 70% of biogas can be produced from any given mass of human waste) (Onojo, 2013). Each cubic meter of biogas contains the equivalent of 6kWh of heat energy, and the same volume of biogas converted to electrical power yields 2kWh (Aqper, 2019). Therefore, the electrical energy produced from that amount of biogas may equal 21TWh, eventually rising with the increasing population.

In a study by Tamal Chowdhury et. al., biofuel production from animal waste has been projected as the solution for animal waste management along with the potential of a new source of renewable energy (Chowdhury, et al., 2020). This study aimed to evaluate biogas production from farm wastes in Bangladesh and presented the potential biological applications for processing the wastes to convert them into biogas. The study demonstrated that the highest amount of livestock waste, approximately 229 million tons, was produced in 2016 and accounted for a total biogas production potential of 16988.97 million $m^{3,}$ which could be converted into $16.68X10^7$ MWh of electricity. This study also presented the suitable conversion technologies as well as mechanisms of biogas production from animal waste and related mathematical equations to calculate the total biogas production. The latest advancements in large-scale biogas production via government and non-government organisations have also been documented in this work. Besides biogas production analysis, this study also demonstrated the environmental impacts of biogas application. A net CO_2 emission reduction of 4.42 million tons could have been achieved over diesel power generation and 29 million tons of biofertilizer. The study also proposed a management plan to improve Bangladesh's waste removal situation. This review also comprehensively outlined the worldwide scenario of biogas production and applications (Chowdhury, et al., 2020).

In addition, the amount of Cattle droppings available from 22 million cows, goats and buffaloes is nearly 0.22 million tons. One ton of dung can produce 37 m^3 of biogas. Therefore, the total excreta can produce 2.97×10^9 m^3 of gas equivalent to 1.52×10^6 tons of fossil fuel or 3.04×10^6 tons of coal[4].

However, this research will not emphasise the potential of using biomass as a power source much since the landmasses already suffer from chronic infertility due to overharvesting and persistent removal of humus.

[4] https://energypedia.info/wiki/Bangladesh_Energy_Situation#Biomass

The refertilising of the soil with the revoked vegetation is complicated according to several failed waste management projects to date. The government intends to return vegetable and other biological waste to the environment to protect the degrading biome (MoE, 2017). Therefore, burning biomass to generate power is still not considered a sustainable option for a vulnerable Bangladesh.

2.6.4 Tidal Power

The tides at Chittagong Division are predominantly semi-diurnal, with a large variation in the range corresponding to the seasons, the maximum occurring during the southwest monsoon. In 1984, an attempt was made by the mechanical engineering department of Khulna University of Engineering and Technology to assess the feasibility of tidal energy in the coastal regions of Bangladesh, especially at Cox's Bazar and at the islands of Maheshkhali and Kutubdia (Roy, et al., 2015). The average tidal range was found within 4-5 meters, and the spring tide's amplitude exceeds 6 meters. From different calculations, it is anticipated that there are several suitable sites at Cox's Bazar, Maheshkhali, Kutubdia and other places where permanent basins with pumping arrangements might be constructed, which would be a double operation scheme (Roy, et al., 2015). However, the schemes are still not considered bankable due to high investment requirements compared to the production efficiency in the Bangladeshi context (Das, 2019).

2.6.5 Hydro Power

Regarding hydropower production in Asian countries, Bangladesh, with a capacity of just 230 MW, is ranked at the bottom of the tally. With a low-lying landscape around most of the area and the critical geopolitical situation among the hill tract regions, it is challenging to increase the yield. Hydroelectricity is a source of clean energy. Bangladesh's only hydroelectricity generation plant situated in Kaptai, Rangamati, was built in 1955 which, was built at a huge human cost through the occurrence of local political unrest, and the government is not interested in repeating it anyway (Parveen & Faisal, 2012). Bangladesh's only recourse is to tap the hydroelectric generation projects in Nepal, Bhutan and Sikkim, India. It has already agreed to invest in hydroelectric power projects in exchange for a chunk of the power produced there (Mamoon, 2019). Bangladesh is now importing 1140MW of electricity from India while importing another 500MW in the pipeline through interconnectivity. Bangladesh, Bhutan, India and Nepal have already agreed to establish hydroelectricity projects through basin-wide water management as part of the region’s efforts to exploit the hydropower sector and use water resources for mutual benefit (Dash & Nakayama, 2019). Under the agreed minutes, the four SAARC nations will likely develop two power projects, including the Sunkoshi-2 and Sunkoshi-3 in Nepal, with a combined capacity of 1,646MW and 1125MW Dorjilung hydropower project in Bhutan, subject to the feasibility study. The concerned authorities should increase their efficiency, negotiating, diplomatic and management skills. Recently, the Bangladesh government has pursued a diplomatic endeavour to import 4000 MW of hydroelectricity from Bhutan by 2030. Regional cooperation for hydropower development can usher in a new era of prosperity in the line of sustainable development for Bangladesh (Mamoon, 2019). Therefore, green power import has been added as an important factor in renewable transition for Bangladesh.

2.6.6 Geothermal Energy

Geothermal energy, in addition to solar, wind, hydropower, and other renewable resources, could aid Bangladesh in resolving concerns like energy scarcity and fluctuating fuel prices in a self-sufficient and environmentally sustainable manner (IRENA, 2019). This energy is readily available but largely untapped; thus, extensive research and field surveys are needed to capture it. Few studies stressed assessing the geothermal potential in Bangladesh to date. According to geological studies con across Bangladesh, some of the potentials of all the sites in the northwest region, including the Singra-Kuchma-Bogra area, the Barapukuria coal basin area, and the Madhyapara hard-rock mine area appear to meet the requirements of binary cycle power plants (Das, 2017). According to a study by Akbar, the predicted temperature is quite variable, ranging from 67 to 153°C, which may refer to a potential low-temperature geothermal field in the Madhyapara area in Bangladesh (Apley, 2011).

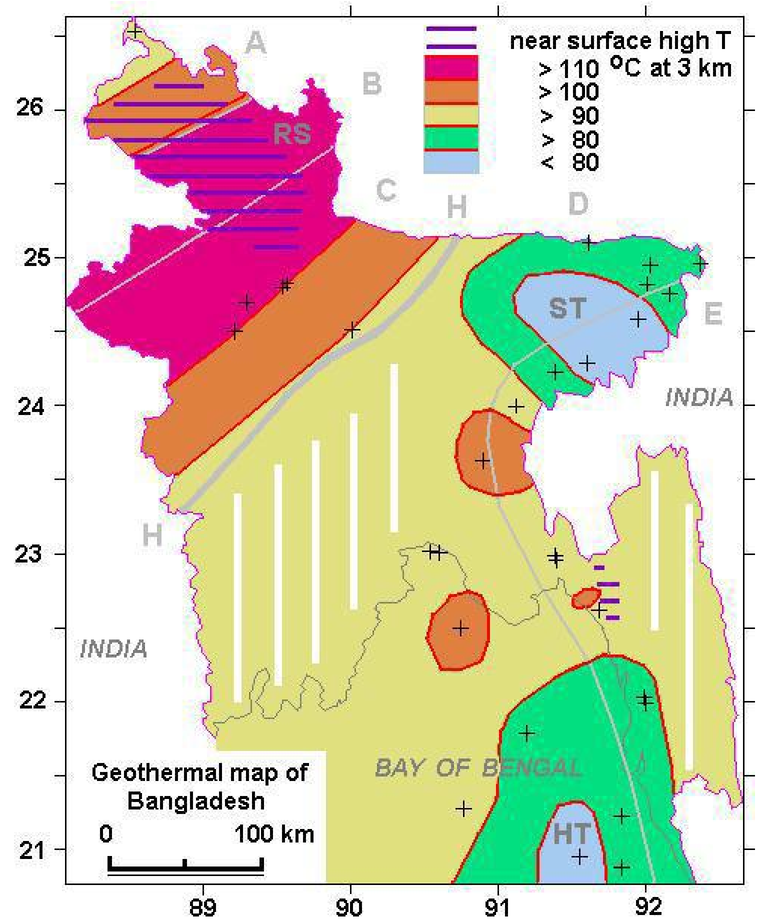

Figure 9: Geothermal map of Bangladesh (Das, 2017)

These spots also have temperature gradients above 30°C/km on bottom hole temperatures above 100^0 C. But an in-depth investigation is necessary before exploiting the resources in a realistic, feasible, and economically profitable way (Karim, Avro and Shahriar, 2018). The process would not start unless the government recognizes the potential of the numerous natural resources suggested by geological studies and takes the necessary steps to develop them. However, geothermal energy is unprofitable in nations without active volcanoes or geysers (Das, 2017). It is one of the biggest obstacles to its usage, primarily due to the complicated and highly capital-intensive exploration phase. That is likely the cause of the current preference among nations for more established renewable energy sources like solar, wind, and hydropower. Nevertheless, since technology has advanced significantly over the past few decades with the development of binary cycle plants and improved geothermal systems, interest in geothermal energy has increased across several nations (EGS)(Das, 2017). Therefore, all nations, including Bangladesh, must contribute to the continuous research and development of geothermal energy since it will benefit all countries and ensure that the earth remains habitable for future generations.

2.7 Systematic literature review on Socioeconomic Capacity Modelling for green power transition in Bangladesh

This section provides the literature review of the backbone of this research: the Socioeconomic capacity modelling for Renewable Power Transition in Bangladesh.

Table 3 Literature Review Protocols

Steps	Key Points/Methods
Review Questions	a) What statements/arguments/studies are available in the existing knowledge pool on Renewable Power Transition Modelling in Bangladesh? b) What are the best possible transition pathways suggested in those studies? c) Are there any papers on socioeconomic/sociotechnical capacity-based transition modelling for Bangladesh? If yes, what do they say?
Quality assessment	No single and generalised method to assess methodological quality exists in the world of scientific research. Therefore, the evaluation should be restricted to studies of an explicit type that are best matched to address the research question of the study (Denyer & Tranfield, 2009).
Data extraction	A typical data extraction form includes the following information references, keywords, abstracts, conclusions, and results (Jesson et al., 2011). However, in addition to that, the arguments relevant to linking Renewable Transition, Developing Countries, Socioeconomic Capacity and Modelling Techniques are included. (Table- 3)
Data synthesis and analysis	Descriptive synthesis developed strata from a detailed examination of all studies. Presentation methods: Tabular sheets, Matrices. Analyses: Content analysis, Qualitative thematic analysis (Braun & Clarke, 2008)

The following diagram (Figure 10) shows how the reviews converge towards the narrowed-down focus:

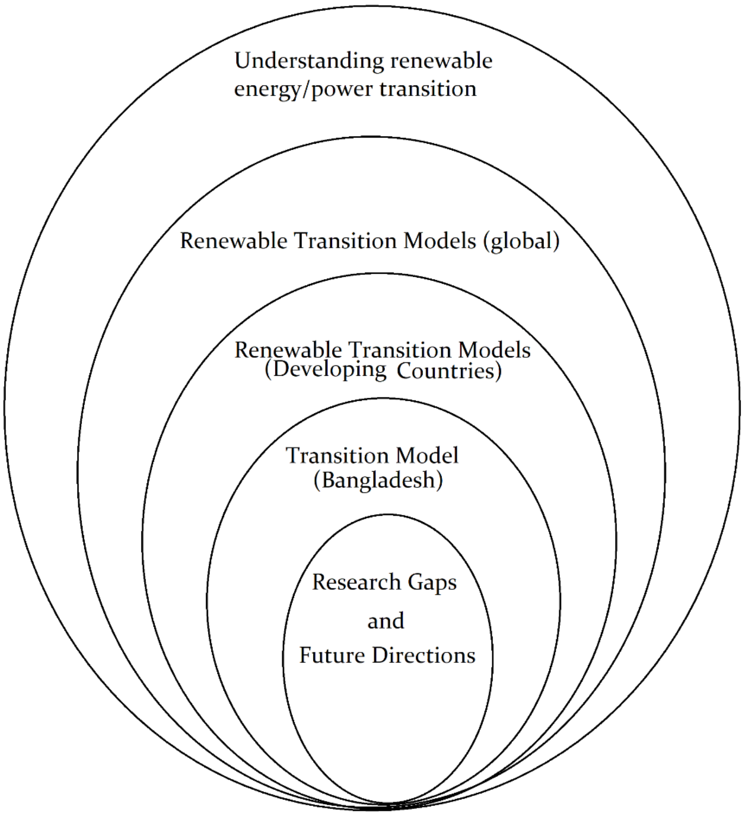

Figure 10 Convergence algorithm of the research focus (Narrowing Down Sequence)

2.7.1 Renewable Transition studies and reality-based text-mining analysis in Scopus (as of 19/09/2020)

The typical data extraction in Scopus below includes the following information on references, keywords, abstracts, conclusions, and results (Jesson et al., 2011). In addition to that, the arguments relevant to linking Renewable Transition, Developing Countries, Socioeconomic Capacity and Modelling Techniques are included.

Table 4: Renewable Transition studies and reality-based text-mining analysis in Scopus (as of 19/09/2020)

Scope	Themes covered in the study (Used in combination or separately)	Number of studies	Remark
Broad	Renewable AND Energy AND Transition	19754	Extensive literature is available on the renewable energy domain. Nonetheless, most of those are based in developed countries and countries with abundant renewable resources. Some developing countries like China, India, Malaysia and Brazil have received concentrated attention. Their demography, green power prospects, opportunities, and geolocations are much more favourable than Bangladesh's regarding greening the power domain.
Broad	Renewable AND Energy AND Transition AND Modelling	8834	Extensive literature is available on renewable energy transition modelling techniques, models, simulations etc. However, most of them are based in developed countries and countries with profuse renewable resources. Some developing countries like China, India, Malaysia, Ghana, Nigeria and Brazil have received attention. Still, their demography, green power prospects, opportunities, and geolocations are much more favourable than Bangladesh regarding greening the power domain.
Converging	Renewable AND Energy AND Transition Modelling Developing Countries	1476	The number of studies considerably narrowed down for the case of the developing countries as cheaper options are available, and affordability in the short term remains the main concern among the regions where 100% power access has not been achieved yet. It shows reluctance or avoidance of the longer-term sustainability issue among developing economies with significantly lower carbon emissions.
Converging	Renewable Energy Transition Modelling Bangladesh	293	Limited studies include the Bangladesh scenario but draw examples or cite other papers on Bangladesh regarding secondary foci.
Converging	Renewable Energy Transition Modelling Developing Countries, Socioeconomic	225	Few don't include the Bangladesh scenario but draw examples or cite other papers on Bangladesh regarding secondary foci.
Converging	Renewable Energy Transition Modelling VAR	168	The Vector Autoregression technique was used in very few modelling studies. However, this method seems pertinent to Bangladesh, as the renewable energy escalation took off only a decade ago. The influential factors may be highly correlated, most of which are available in a time-series fashion.
Narrow	Renewable Energy Transition Modelling, Developing Countries, Socioeconomic capacity, Bangladesh	17	None of these studies is concerned with the green energy transition's socioeconomic capacity.
Narrow	Renewable Energy Transition Modelling, Developing Countries, Socioeconomic capacity, Bangladesh, VAR	6	None of these studies is concerned with the green energy transition's socioeconomic capacity modelling for Bangladesh.
Focus	Renewable Energy Transition Modelling, Developing Countries, Socioeconomic capacity, Bangladesh, Vector autoregression	0	The proposed study will conduct the socioeconomic capacity modelling for the renewable power transition in Bangladesh.

2.8 Energy Transition Model: Definition and Implications

Transitions in most of the dynamic systems of human society and civilisation exhibit many notable characteristics, including orderliness, symmetry, analogy, trends etc, that have the potential to develop insights and understanding about the dynamics along with logical inferences for reliable forecasting on those systems (Li, Trutnevyte and Strachan, 2015). If transitions can be made to appear 'before eyes' in a simulated environment, a better and more precise understanding of the mechanisms underlying change may be generated (Chappin, 2011). To run such a simulation, mathematical or statistical modelling is a dependable, practicable and widely used instrument that not only uses the realistic logic behind the transitions but is also capable of exhibiting the extent of the influence of the drivers, factors or parameters used to describe the transition facilitating the scopes for sensible forecasts (International Renewable Energy Agency, 2017). Such simulations may enable the stakeholders to improve the quality of actual decisions made regarding the existing and upcoming energy infrastructures for reasons of environmental sustainability, accessibility, affordability or security of supply and other influential factors that drive transition (Chappin, 2011).

Change in large systems, such as electrical energy infrastructure systems, is the central topic of the scientific literature on transition models (Geels, 2002) and transition management (Rotmans, 2003; Loorbach, 2007). These research fields have grown considerably in the 21st century (Bolwig *et al.*, 2019). This paper by Bolwig et al. also suggests that despite all the research efforts, applying transition management in the real world is not trivial. One approach is to use simulation models, but simulations have yet to be explored more carefully, deeply, and extensively as they produce highly stochastic results. If transitions in simulation models can be captured precisely, new insights may be contributed to the body of knowledge on transitions and transition management(Shinohara and Georgescu, 2011). In particular, the stakeholders who are likely to be involved with power generation and supply should have some deeper insights into these models so that they can make decisions, plans and strategies to regress carbon emissions and exploit the socioeconomic benefits from this sociotechnical paradigm shift (J. Solé, et al., 2020).

2.9 Energy Transition Models: Past Studies

Why are different kinds of modelling approaches needed to address the transition diversity? The next paragraphs tried to answer the question.

Granado et al.'s meta-analytical review on energy transition notes that a plethora of literature has already been added to the knowledge pool regarding energy system transitions, their modelling, simulations, and interpretations (Granado, et al., 2018). In the same paper, the authors found that the number of studies and associated publications has recently increased. Another meta-analysis on Energy Transition Models provides a clear comparison of the methods. It characterises them based on seven basic criteria of energy models, including purpose, methodology, analytical approach, geographical coverage, mathematical approach, time horizon, and data requirements (Gholami *et al.*, 2020). This paper aims to deliver to policymakers and associates the precise and supportive foundations for selecting appropriate techniques based on the most frequently used intensive methods published between 1960 and 2018. However, renewable energy's penetration prospects and modes of transition dynamics are highly diversified due to the spatiotemporal variability of the resources, the disparity in affordability, and diverse sociopolitical and socioeconomic grounds (Baker, et al., 2021). Mapping diverse visions of energy transitions, Noel Longhurst and Jason Chilvers argued that regional variability is quite evident in such transition diffusion and different approaches and techniques are needed to model such transitions for different geolocations with different socioeconomic and technical features to grasp the endemic scenarios (Longhurst and Chilvers, 2019). This insight suggests that modellers should select and apply different techniques and approaches to construct the individual modelling framework for different regions. Reviewing the past literature, this section tries to find the rationale behind framing and simulating the socioeconomic capacity modelling for the renewable power transition in Bangladesh, along with focusing on the selected methodology for such an endeavour.

Exploring different renewable transition models that considered different features in different contexts, it is noticed that economic viability played the strongest role in selecting renewable and fossil-fuel systems (Painuly, 2001; Steinhilber, Wells and Thankappan, 2013). In the case of Brazil (Fraundorfer and Rabitz, 2020) and Iceland 2019, where hydropower and geothermal potential is abundant, respectively and comparatively advantageous in terms of technical efficiency and economy, the generation has been strongly supported and propelled by the governments. In contrast, despite having abundant solar potential, Saudi Arabia is still sticking to fossil-fuel-powered systems because of the financial advantages of the higher rate of return and system lock-in inertia (Al Khars *et al.*, 2020). A similar situation is demonstrated amongst many other countries where they are poorly utilised despite having exploitable renewable resources with comparatively less bankability (Burke, 2020). In India, the highly aspiring solar dreams are recently instigated and propelled by a wave of ideological motivation from ancient traditional views and culture[5]. In Bangladesh, policymakers declared that the country would significantly expand its renewable generation when it becomes more financially viable as it emits a negligible amount of carbon per capita compared to the developed world (Alo, 2020). Therefore, the renewable transition is a highly stratified domain where context is a critical factor to be considered.

2.10 Modelling the energy transition

Energy System Transition Models deliver the conceptual idea of paradigm shifts in power generation systems. Multifaceted sociotechnical factors and parameters that drive these enhance the capacity to make rational and precise inferences for planning and implementing energy-related agendas, which may extend from local to global contexts (Chappin, 2011). Existing works on modelling the different dimensions of the energy transition in different ways are reviewed in this section of the report to understand why models focus on certain features or parts of the energy system. In addition, this section tries to identify the gaps in the earlier studies to be addressed in this thesis.

2.11 Different Approaches for Modelling Energy System Transition

This section is a part of the literature review on the study of 'The Penetration of Renewable Power in Bangladesh'. In the nexus to answering the research question on assessing the extent of influences of different socioeconomic and technical factors and parameters (namely variables) on the renewable power transition, the study decided to construct, simulate, and analyse a model to forecast the future sociotechnical capacity of Bangladesh transitioning towards renewable power. The model aims to support policymakers and planners to make informed decisions and prioritise implementation strategies according to their escalating socioeconomic and technical capacities. This study proposed constructing and simulating the model using the vector autoregression logistic non-linear technique. It incorporated the independent variables, namely renewable power budget, foreign aids and grants for such ventures, energy storage price, per capita income as economic affordability, renewable power system efficiency and smart grid expansion as technical capacity parameters, direct green power import from neighbouring countries, land acquisition of large solar plant, PV power price, carbon taxation, subsidisation etc. The dependent variable is the maximum achievable renewable power in TWh at a certain time (year). Now, this section will try to find the gap in the past literature regarding:

- Energy system transition modelling for Bangladesh
- Sociotechnical capacity modelling for Simulating Renewable Power Transition in Bangladesh
- Existing energy system transition modelling was undertaken with a vector autoregression logistic non-linear technique.

Sustainable Development Goal no. 7 outlines a target by 2030 to ensure universal access to affordable, reliable, and modern energy services and substantially increase the share of renewable energy in the global energy mix (Maruf *et al.*, 2020a). Adhering to that, Bangladesh has taken multiple initiatives in harnessing

[5] https://www.bridgeindia.org.uk/religious-groups-are-adopting-renewable-energy-in-india-but-more-can-be-done/

renewable power and using it to provide access to modern energy for millions of people. It has also set a target to install 10 GW generation capacity from renewable resources by 2041[6]. In the meantime, the policymakers also understand that there may be a dramatic fall in the renewable power price in the future that may surpass the carbon-emitting systems regarding economic efficiency over the next decade (New Energy Outlook, 2015). If the country delays exploiting the relative advantage of such green systems at that time, it may result in transition shock or disruption unpreparedness, severely affecting the overall economy as energy access multiplies nearly all socioeconomic developmental indices (Farag and Komendantova, 2014). Therefore, the government seeks to determine the optimum timebound pro-green energy policy through periodic adjustments and amendments for the future. This thesis intends to provide assessments of the maximum extractable renewable power within the territory of Bangladesh, along with some comments on the extent of pragmatism considering its progressive sociotechnical or socioeconomic capacity.

2.11.1 Important and pertinent studies converging towards the Renewable Power Transition Modelling

The paragraphs below detail several significant and pertinent studies with their findings, relation to the incumbent research and the possible research gaps. It will also converge its focus to the transition in Bangladesh and the modelling approaches used so far in the past literature.

Reality-based text-mining analysis in Scopus (as of 19/12/2020) suggests that a large body of work is available in the domain of renewable energy transition. Even so, most of these are based on developed countries and/or countries with abundant renewable resources (Di Sbroiavacca et al., 2014; Ćetković and Buzogány, 2016; Balthasar, Schreurs and Varone, 2020; Robertson Munro and Cairney, 2020). Some developing countries like China, India, Malaysia, and Brazil have been considered more intensely. Still, their contexts are much more favourable compared to those of Bangladesh regarding greening the power sector influenced by economic affordability, resource availability, demography, and technical capacity (Moallemi et al., no date; Lim and Elias, 2006; Cai and Aoyama, 2018; Khondaker, Moazzem and Ali, 2019; Fraundorfer and Rabitz, 2020).

Several works on the features of the transition studies and modelling techniques classified the available methods. According to the review of renewable transition models by Hall & Buckley, three main modelling approaches present the interactions between the technological details of the energy systems, the economy, and the environment (Hall & Buckley, 2016). First, the top-down macroeconomic modelling emphasises the aggregated economic-wide view and incorporates the power generation technologies with less detail through aggregated functions within a large macroeconomic system. The second, bottom-up approach, uses models with a technology-rich and detailed representation of the energy system but does not include the interactions between the energy system and the broader economic system. Thirdly, the hybrid approach integrates bottom-up models' detailed energy technology representation into a top-down macroeconomic model (Hall & Buckley, 2016).

The top-down approach to address the macro- and microeconomic behaviour is the application of computable general equilibrium (CGE) models (Capros et al., 2013). CGE models are top-down models firmly grounded in neoclassical microeconomic theory and consist of the agents in an economy (households, producers/firms, government) and the markets for goods and factors. Households and government maximise their welfare, and the producers maximise their profits (Chen, Chen and Ma, 2021). The agents interact in the markets by supplying or demanding goods or factors. A price mechanism reaches market equilibrium. Prices can adjust to find an equilibrium between supply and demand (Crespo del Granado et al., 2018; Chen, Chen and Ma, 2021). However, considering the electricity economics of Bangladesh, a strong government

[6] https://www.sdg.gov.bd/page/indicator-wise/5/442/3/0#1

regulatory authority is presently overseeing power pricing. This is still not a free-market commodity impeding the spontaneous equilibrium among the influential agents (Taheruzzaman and Janik, 2016). Therefore, a top-down approach may be applied in the transition landscape of Bangladesh but at the expense of the free-market equilibrium conditions, which hinders its applicability. It implies the necessity of more flexible, reliable, and befitting techniques for Bangladesh's context.

A study found that when the government of Bangladesh, aided by foreign donors, implemented schemes like incentivisation of solar panels for rural solar home systems and promotion of grid-tied solar generations by motivating independent solar power producers, the renewable generation escalated rapidly after 2011 (Samad et al., 2016). Before that, renewable power generation was stagnant for several decades. Therefore, the timeline is also a remarkable point where the period from 2010 was considered significant as the base data for constructing the model. It also implied that government intervention in the market and foreign support played crucial roles here.

The hybrid approach tends to develop more wide-ranging energy and economic modelling approaches adopting all the features of the previously mentioned classes. A major drawback of top-down-bottom-up linkage can be the inconsistency in the behavioural assumptions used in the models. Therefore, it is necessary to calibrate the top-down model to the results of the bottom-up model to resolve these inconsistencies. Measuring the goodness of fit to the real data can be an optimum calibration method. Hybrid models are now widely used to conceptualise and exhibit energy transition pathways. Various multifarious variables are used to obtain practicable outcomes for any region with versatile features regardless of the economy, geolocation or technology (Triyanto et al., 2017). The tumultuous political circumstances further complicate the situation, where renewable penetration is decided as a major government concern. Bangladesh is an overpopulated country with prolonged poverty and scarcity of natural resources, with transition drivers of both top-down (Carbon Tax, Subsidy, Power Pricing etc.) and bottom-up (Economic Affordability) characteristics. Therefore, a multidimensional approach is needed to capture its prospective transformation scenarios. Considering all these issues, a hybrid approach has been considered in this study where the macroeconomic features of Bangladesh, like economic affordability, budgetary allocation, incentivisation, foreign grants, and aids etc., are incorporated along with the technical features like smart grid propagation, system efficiency, energy storage etc. Some concise models of Bangladesh's renewable transition pathways used the same approach (Bhat et al., 2019; Gulagi et al., 2020a; Hossain et al., 2020). The proposed model for this work aims to select and compile the most contextually significant ones and include more variables that are deemed plausibly significant, widening its simulation horizon.

Many modern researchers developed innovative approaches for modelling energy system transitions. Most of them are found to have hybrid modelling attributes. Still, any of them can be attributed to either of the previously mentioned three groups concerning the conceptual or structural frameworks (Crespo del Granado et al., 2018).

The literature describes several hybrid styles for connecting current top-down models with bottom-up models or for having more multi-model/sector viewpoints (Hafner et al., 2020). A classic illustration is the MESSAGE-MACRO model that connects the MACRO model to the MESSAGE electricity supply model (Messner and Schrattenholzer, 2000). In it, the scenarios are compared in terms of GDP, energy supply and demand and energy prices, which are considered variables in this thesis model. Other examples were developed by (J.-C. Altamirano & Vielle, 2012), who couple the Swiss MARKAL residential model to GEMINI-E3, a global CGE (computable general equilibrium) model, or, with a more detailed implementation of the energy sector, the Emission Prediction, and Policy Analysis (EPPA) model developed at MIT (S. Paltsev & Babiker, 2005). The EPPA model is a recursive-dynamic multi-regional general equilibrium model of the world economy devised to develop forecasts of economic growth or similar trends. The model includes many energy supply technologies and is linked to a climate-land ecosystems model, but it only emphasised free demand-supply mechanism which is often absent in developing country context like Bangladesh. Bangladeshi power sector business is heavily regulated and operated by state-owned agencies.

A recent approach of linking the methodologies mentioned above for energy-economic analyses at different geographical levels named pymedeas represents a step forward to the current models' state of the art because pymedeas is a model that mixes economy and energy-resources analysis using a novel coupled Input-Output energy-resources methodology (Solé et al., 2020a). The novelty of Pymedeas within the existing modelling approaches also lies in the new scenarios defined to frame the model runs. Different scenarios, which define initial hypotheses on key parameters and system evolution hypotheses, can be fed to the model as input data. The scenarios act as a framework that helps understand the links between the model's exogenous variables and endogenous variables like GHG emissions and the energy-economy evolution and, thus, climate change impacts on the economy. The key exogenous variables that comprise each scenario include those related to the expected rate of deployment/implementation of RES, transport electrification, efficiency improvement, population growth or economic growth (Solé et al., 2020a). Though seeming rational and useful, this method has yet to be used in the case of any developing country to date, let alone in a Bangladesh context due to its newness. The country still emits very little carbon compared to the highly industrialised countries. Therefore, the policymakers and lawmakers of Bangladesh, the key entities behind the green power transition, are not much concerned about escalating green power generation to merely cut down carbon emissions (a key variable in the Pymedeas model).

Bottom-up approaches use a detailed and technology-rich model without interactions with the rest of the energy system, often in a MARKAL (Market-Allocation) model (Zonooz *et al.*, 2009). It is a widespread modelling technique for analysing the supply side of the energy system. The simplest version is a bottom-up linear programming model, where multiple energy supplies and demands are depicted based on technology costs and technical characteristics (e.g., investments, operating costs, capacity utilisation, and fuel use efficiency). The technology mix results from minimizing the total system cost of energy supply based on a given energy demand, costs of running these technologies, and costs of investments in additional capacities or new technologies. In its basic form, MARKAL has several limitations (Crespo del Granado *et al.*, 2018; Solé *et al.*, 2020b). In these models, the energy demand is often exogenously given and does not adjust if energy prices change. Other important drivers, like the impact of GDP or income growth on energy consumption, are missing, which have been addressed in this work. To fill these gaps in this thesis, demand is separately projected and used as an endogenic variable adjustable between it and the prices of renewable power or fossil-fuelled electricity as they were found to have profound correlations (Bussar *et al.*, 2016; Nath, Barua and Mohammad, 2019) amongst themselves. However, only one study was found in Bangladeshi context that used MARKAL. In the paper (Mondal, et al., 2014), different policy scenarios were developed for the analyses of the power sector. Different setups were analysed from 2010 to 2035 using MARKAL. The highest installed capacity of solar PV is observed in the Null Coal Import scenario of about 41GW, and electricity generation is 84 TWh. The renewables share in total installed capacity in 2035 is about 41%. It addressed the 100% renewable potential issue via the most conservative approach considering the current growth rate and mode of green power in Bangladesh. It also focused on classic resources' transitions based on their business-as-usual trends. It used the MARKAL tool, Nonetheless, it considered only 25 years' landscape narrowing its pertinence and applicability as MARKAL model requires a longer period to demonstrate a plausible simulation. Whereas, the recent renewable escalation in Bangladesh took off only throughout the last decade after a long stagnation for six decades (Figure 45).The limitations of the MARKAL model can include the simplification of complex systems, potential for inaccuracies in input data, and assumptions made in the modelling process (Krzemień, 2013). All these limitations are likely to be exhibited while modelling transition in Bangladeshi context. Several endemic variables may occur due to unique geographic (See section 2.2) and demographic (See section 2.13.7) features of Bangladesh which are not pertinent to other countries. These features have significant influence over the sociotechnical capacity for transition of the country making its dynamics highly complicated. The input data quality regarding socioeconomic indices and other variables found from different agencies concerning developing countries are often requires refinement and deeper scrutiny (IMF, 2019). Therefore, modelling approaches with more flexibility, and less sensibility to data quality are required for Bangladesh context. The forecast of any socioeconomic/sociotechnical index or variable trends in a developing country context, higher level of stochasticity consideration is essential (Qin, 2022). MARKAL models are often vulnerable to handling stochasticity and weak in generating credible forecasts or modelled outcomes (Krzemień, 2013). Evidentially the paper by Mondal, et al., 2014 has already demonstrated a lot of deviation from the predictions by now. Considering all these, MARKAL is not a suitable option for modelling the sociotechnical capacity for transitioning the power sector of Bangladesh.

Linear modelling techniques are the simplest but sometimes can deliver good fit depending on the independent variables tends and correlations among them (Li, 2013; Perez et al., 2019, Hans, 2018; Reeves et al., 2014; Kerr et al., 2020). These models typically consider factors such as energy demand, technological advancements, policy changes, and economic considerations to project how the energy transition will unfold over time in linear fashion (Diéguez et al., 2022). National Committee Bangladesh produced a linear transition model (NCBD, 2017) that expected by 2041, the approximate electricity demand would be 490 TWh in which renewable energy contributes 55%, natural gas 37%, and others have 8% share. Batteries would be used as storage technologies with a capacity of 78 TWh. This study discourses on the transition in an ambitious mode though it concludes with an array of realistic transition prospects. The demand projection ignored the possibility of the use of conservation and efficiency that may significantly change the scenario. The rapid natural gas exhaustion was not addressed in detail. The model parameters incorporate only the transition and business trends of different kinds of energy resources. The sociotechnical capacity for the transition is not addressed which is stressed heavily by the stakeholders of the transition in Bangladesh.

The LUT (Lappeenranta-Lahti University of Technology) Energy System Transition model, a high temporal-spatial resolution linear optimisation tool, is used to model an energy and power system transition (Bogdanov et al., 2019). Gulagi, et al. (2020) analysed energy transition pathways in the context of Bangladesh using the LUT tool. Four scenarios to analyse various energy policies were demonstrated on the present and alternative renewable energy-based policies, with and without the cost of greenhouse gas emissions. The simulations show that emissions costs accelerate the transition towards an entirely renewable system. Nevertheless, the omission of these expenses does not exert a substantial impact on the energy system, given that renewable sources would still account for 94% of the total electricity output by the year 2050. The prevailing policy scenario exhibits a notable escalation in power and greenhouse gas emissions costs, commencing from the year 2025. The research findings suggest that countries such as Bangladesh are susceptible to significant and intricate national risks, resulting in various vulnerabilities such as elevated power expenses, heightened greenhouse gas emissions, energy insecurity, and diminished sociopolitical trust if current energy policies are pursued. However, directing attention towards indigenous renewable resources has the potential to alleviate this vulnerability and yield socioeconomic advantages. This robust study addresses Bangladesh's 100% renewable energy aspirations and prospects, suggesting many realistic policy options. Nonetheless, it focused mainly on the technical and spatiotemporal aspects of solar energy to model the transition pattern ignoring the socioeconomic affordability and absorptivity towards the massive green power of Bangladesh, which is very likely to play a vital role in the transition. The incumbent thesis will address that.

Highly contextualised modelling techniques were developed through a few research around the world. ATLANTIS_India, a distinctive technoeconomic simulation model was developed at the Institute of Electricity Economics and Energy Innovation/Graz University of Technology (Bhat, et al., 2017). This model is specifically designed for analysing the electricity system in the Indian subcontinent region. Using it, a technoeconomic model-based analysis of the renewable energy transition in the Indian subcontinent region (Bhat, et al., 2019) focused mostly on India, formally the Republic of India, a country in South Asia that is the world's second-most populated, seventh largest, and most populous democracy. As a 'developing' nation, it is amid a unique predicament in which it must manage its energy transition to carbon-free energy alongside its ongoing economic growth. Regarding the agreed-upon COP 21 and SDG 2030 targets, India has created several clean, renewable energy-based energy strategies (Bhat et al., 2019). India's long-term renewable energy aspirations rely heavily on solar photovoltaic (PV) and wind power capacity due to the numerous obstacles to developing major hydropower capacities within the country. With a far slower rate of development in transmission infrastructure and the current state of regional energy networks on the Indian subcontinent, these big changes in India could have serious technical and economic repercussions for the entire interconnected region. The scope of the model encompasses the energy systems of India, Bangladesh, Bhutan, Nepal, and Sri Lanka. Its purpose is to assess a hypothetical scenario in which there is a planned increase of around 118 GW of solar photovoltaic (PV) and wind capacity in India, with the target year set at 2050. The simulation results show the discussed strategy's positive and negative techno-economic impacts on the overall electricity system while suggesting workable solutions. It is a very useful paper for the incumbent study as green power export from the neighbouring states will play a crucial role in greening the power sector of Bangladesh due to its limited resource capacity. The simulation algorithm will be inferred and extended to the context of capacity modelling of renewable escalation in Bangladesh based on socioeconomic and some technical parameters. Some highly influential transition factors were not considered in this model, like technical efficiency or land availability, which are pertinent to the Bangladeshi context. These gaps are addressed in this study.

The relationship between Demand-Side-Management and the transition for a model is crucial, as effective demand-side management can play a significant role in facilitating this transition (Hamwi, et al.,2019; Ali, et al., 2020). By actively engaging consumers, utilities, and other stakeholders in managing their energy usage, DSM can support the integration of new technologies and business models, promote energy efficiency, and enhance grid reliability (Lizarralde, et al., 2019). Imran Khan (2019) focuses on customer-centricity in DSM, with or without the integration of smart technologies such as smart grids, which has been insufficiently directed towards the developing world in terms of strategy development. The primary factors contributing to this issue have been the absence of suitable technology and the financial burden associated with capital costs. Significantly, alternative demand-side management (DSM) solutions necessitate minimal or no financial investment for implementation and yield prompt outcomes. Among these tactics, the energy-saving behaviour of residential occupants stands out as a noteworthy example. This research investigates the viability of energy-saving behaviour as a demand-side management (DSM) method in the least developed economies, with a specific emphasis on Bangladesh. According to the existing body of literature, it has been indicated that the adoption of energy-saving behaviour has the potential to result in a reduction in energy consumption of up to 21.9%. However, the potential of DSM schemes seems undermined in the national DSM program of Bangladesh. The Energy Efficiency and Conservation Master Plan (EECMP) of Bangladesh (a DSM program) shows that efficiency enhancement in the use of domestic devices could reduce electricity demand in the residential sector by about 28.8%, but this does require a long time to be implemented. In contrast, the incorporation of energy-saving behaviour as a demand response technique in residential settings, in conjunction with the Energy Efficiency and Conservation Measures Programme (EECMP), has the potential to yield a demand decrease of up to 50.7%. While the results of this study are limited to Bangladesh, they can serve as valuable recommendations for policymakers in other developing countries now engaged in the development of national DSM strategies. Demand-side management is crucial, considering the temporal variability in renewable supply. However, the incumbent research focuses on the overall renewable power generation in the modelling.

The implementation of smart grid can play a significant role in accelerating the efficient use of renewable energy from fluctuating resources (Li et al., 2019, Ahmed, 2019; Edson, 2020). In general, a smart grid optimises electric power distribution system performance using sensors, communication systems, computational capabilities, and control mechanisms. Integrating sensing, communication, advanced cognitive processes, control, and feedback mechanisms develops a system's intelligence (Acakpovi *et al.*, 2019; Bandeiras *et al.*, 2020; Maruf *et al.*, 2020). Many functions can optimise bulk generation and storage, transmission, distribution, and consumption in an ideal power system (Molina et al., 2019). It could boost energy efficiency and dependability. It will also reduce pollution, conserve resources, minimise expenses, enable efficient responses to potential risks, maximise safety, and provide high-quality power to meet 21st-century demands. Only one study concerning this issue over Bangladesh was found. An Overview of Smart Grid Technology in Bangladesh: Development and Opportunities (Ali et al., 2011) suggested that it would help digitise its electrical infrastructure. This paper presents the idea of the smart grid approach in Bangladesh. Bangladesh is new to smart grids. Bangladesh's electricity grid is complex and primitive. A smart grid may be a better way to simplify and improve the current system. Bangladesh has frequent load-shedding. Smart grid technologies solve the problem. The system can recognise, compute, and allocate electricity based on load requirements. Even during load shedding, clients will have access to grid-supplied electricity. The main objective of this paper is to discuss the requirement of a smart grid from the perspective of Bangladesh, which may be an effective solution to handle the contemporary power crisis. No significant paper with numerical data was found in the existing knowledge pool. Therefore, this study must collect the latest data on the government's future work plans regarding Bangladesh's smart grid technology aspirations.

Using tools like GIS and multicriteria decision analysis (MCDA), some models were generated for optimising land use when land is critically available in the studied context (Molina Bacca et al.,2020). “Optimal land use and distributed generation technology selection via geographic-based multicriteria decision analysis and mixed-integer programming” (Molina Bacca, Knight and Trifkovic, 2020) is a significant paper where in the future smart grid environment, microgrid placement and sizing have received interest, particularly in Future Bangladesh. This study introduces a multi-scale optimisation approach to predict microgrid configuration, capacity, and location. This model is used to a Southwestern Ontario municipality. The suggested methodology considers the project's net present value, the grid's power balance, the maximum capacity of existing substations, and the geographical feasibility of installing a microgrid. Two steps solve the problem. To determine the best locations for distributed energy resources (DERs), a GIS/MCDA study is performed. Following the GIS and MCDA findings, a mixed integer optimisation model is used to determine the capabilities and final deployment sites of Distributed Energy Resources (DERs). In conclusion, this paper analyses three scenarios to determine how retail price, microgrids' minimal demand contribution, and available land affect renewable energy initiative design, cost, and distribution. The proposed model uses spatially detailed socioeconomic and biophysical data to determine distributed power generator sizing and distribution and optimal land use. The methodology was supposed to be relevant across situations and locations. This study's method locates microgrid component installation sites. GIS and Boolean multicriteria decision analysis accomplish this. This first stage produces fixed places based on local characteristics, including social, environmental, and economic aspects. GIS and MCDA data reveal potential Distributed Energy Resource (DER) locations. Location surface area and substation proximity are included. These data are used in an optimisation model to determine the ideal number and size of DERs for each producing location. The area of Bangladesh is so small, and the insolation is so uniform (due to tropical geolocation) that the effect of spatiotemporal variability on solar power generation across its landscape is not very influential. Nonetheless, from the sensitivity analysis made in this study, it was possible to deduce and confirm that the methodology proposed allows the decisionmakers to estimate the minimum land needed to install a microgrid of a certain producing capacity. The results confirm the proposed approach's effectiveness in determining optimal land use and configuration of microgrids. All 493 subdistricts of Bangladesh are intended to have one solar park, each with a microgrid for that particular subdistrict. The knowledge from this paper may be useful for precisely understanding those projects.

Electricity Consumption and Economic Growth exhibited causal correlation among myriad of studies (Pfenninger, Hawkes and Keirstead, 2014; Shah *et al.*, 2020; Sohag *et al.*, 2020). However, core research is scare in the Bangladeshi context where only one was found. In that (Ahamad & Islam, 2011), the authors examined the causal relationship between per capita electricity consumption and the per capita GDP of Bangladesh using the vector error correction specified Granger causality test to search their short-run, long-run and joint causal associations from 1971–2008. Empirical results show a short-run unidirectional causal flow from per capita power use to GDP without feedback. Electricity use directly influences Bangladeshi economic activity due to positive short-run causation. Joint causality results match short-term results. By contrast, long-run results show a bidirectional causality from electricity expenditure to economic growth with feedback. Considering its planned growth strategy and complicated power and energy sector, these results can provide central policy insights to design immediate and long-term growth prospects for Bangladesh. Given the importance of accessing electricity for accelerating per capita GDP in the short and mid-run, higher investment in power can be suggested. However, it can also be viewed that Bangladesh could target power generation from other non-conventional sources such as solar, hydro and wind power in the short run, even though such initiatives may be a little more costly in the short run. On the other hand, there is a need to provide favourable fiscal incentives and raise private entrepreneurs to develop Bangladesh's power sector eventually. Still, given the weak electricity situation in Bangladesh and the desire to become a middle-income country, which is envisaged in Vision 2021, Bangladesh should build cost-effective power plants exploiting its large coal reserve, which now supplies only a small portion of power generation fuel. Economic affordability has been considered a pivotal factor in renewable penetration in Bangladesh across the incumbent study, as there are still cheaper options than solar power here. It is also considered a primary variable with a multiplier effect in the proposed model that correlates to several other variables. The model rules out those correlated variables to reduce the multicollinearity problem. This thesis also strongly advocates for planning power generation strategies for Bangladesh following its progressive socioeconomic affordability and feasibility rise, particularly in deciding on a green transition plan. The power structure here is still developing, and modern energy access is scarce.

Many existing technical feasibility and modelling studies in the energy field are criticised for their limited treatment of societal actors and socio-political dynamics, poor representation of the co-evolving nature of society and technology, and hence an inability to analyse sociotechnical change (Li, Trutnevyte and Strachan, 2015). At the same time, prominent conceptual frameworks of socio-technical transitions that address these elements are often found to be difficult to operationalise in quantitative energy analyses that meet policy development requirements. However, a new energy modelling paradigm for integrating quantitative modelling and conceptual sociotechnical transitions has emerged. The proposed model rationally comprises these constituents to a significant extent.

An important work on "Modelling energy transition pathways" (Bolwig, et al., 2018) discusses how quantitative modelling of energy scenarios for sustainable energy transition pathways can be made more pragmatic by considering insights from the sociotechnical and related literature (Bolwig, et al., 2018). The proposition is that an enriched modelling approach would focus not just on technology development and deployment but also on feedback loops, learning processes, policy and governance, behavioural changes, the interlinkages between the energy sector and other economic sectors, and infrastructure development. The paper discusses a range of socio-technical concepts with a view to how they can enrich the understanding and modelling of overly complex dynamic systems, such as flexible energy systems with high shares of variable renewable energy. In this context, the application of system dynamics modelling (SDM) for analysing energy transitions is also introduced by describing the differences between SDM and a traditional modelling approach that uses econometric and linear programming methods. A conceptual framework for this type of modelling is provided by using causal loop diagrams. The diagrams illustrate the endogenous approach of SDM – understanding and modelling the structure of a system, which is responsible for its dynamic behaviour (Bolwig, et al., 2018). SDM can also demonstrate the co-evolution of economic, policy, technology, and behavioural factors over sufficiently extended periods, which is necessary to analyse transition pathway dynamics. The paper summarises how socio-technical concepts can be approached in SDM and why they are relevant for analysing flexibility in energy systems. From a computational point of view, combining SDM with a technologically detailed energy system optimisation model should be a way forward for achieving more realistic, non-linear quantitative modelling of sustainable energy transitions (Bolwig, et al., 2018). The influential factors used in the transitional modelling for the incumbent study are mostly socioeconomic and sociotechnical ones directly correlated to the policy decision in Bangladesh's energy transition. That is why it is a crucial paper for the Bangladeshi context, and its knowledge has been used while analysing and selecting the variables. The regression-based multiple-equation modelling used in this study has a deep similarity with the SDM but with a deviation in selecting the array of variables due to the context.

The language of systems can help make sense of the interconnectedness of key actors, the 'emergence' of outcomes from large numbers of interactions, and the proposed transformation – by many governments - towards sustainable energy systems (De Bot, Lowie and Verspoor, 2007). Munro and Cairney reviewed the language of systems can be incredibly useful when defined clearly (Robertson Munro and Cairney, 2020). However, 'whole systems analysis' and 'systems thinking' is often too vague to guide this project well. To explore these issues in depth, it is shown how frequently they arise in UK energy policy research and their impact on policymaking. First, the systematic review shows how researchers present ambiguous or inconsistent stories in which the role of policy and policymaking is unclear when they describe energy systems. Second, the UK and devolved governments often use the language of systems to propose paradigmatic energy policy change but refer to a metaphor rather than academic insights. Third, three ways to clarify energy transitions and policy concerning sociotechnical, complex, and social-ecological systems were delineated. This study delivers a profound insight into the significance of socioeconomic and sociotechnical capacities in causing the transition. It discussed their driving force to accelerate the transitions across different systems, which is highly pertinent to the foundational basis of the modelling of the incumbent research.

The consideration of the rise in energy demand is more crucial in the developing country context than that of the developed country while modelling the transition (Guha, et al., 2016). It is because of the demand saturation amid the developed states caused by stagnant population and economic growth which is not the same among the emerging economies (Masuduzzaman, 2011). A study titled "Modelling and forecasting energy demand in rural households of Bangladesh" (Debnath, et al., 2015) demonstrated a significant rise in energy demand in the future. In the case of the highest demand, the number can be three times that of 2010. If the population, GDP, access to grid electricity and energy use awareness are not monitored and controlled, the demand rise could be devastating, considering the unmet demand in 2010 as a reference point. Even the optimal pathways suggested an approximately two times greater energy demand in 2050 than in 2010. This model provided an opportunity to focus on the detailed power use in households of rural Bangladesh and would work as a powerful tool for the future energy policymaking process for rural Bangladesh. Studied in the Bangladesh context, this paper provides some insights into power demand forecasting and its modelling techniques. However, estimating the rise in demand seems unrealistic as it has already surpassed the forecast amount in 2021. It occurred due to the exclusion of several driving factors that contributed to the rise. Nonetheless, the ideas are still significant in framing the model for forecasting demand.

The National Committee Bangladesh delivered another study that concluded, by 2041, the approximate electricity demand would be 490 TWh in which renewable energy contributes 55%, natural gas 37%, and others have an 8% share (NCBD, 2017) and where batteries would be used as storage technologies with a capacity of 78 TWh. This study discourses on the transition in an ambitious scenario though it concludes with an array of realistic transition prospects. The demand projection ignored the possibility of energy conservation and efficiency that may significantly change the scenario. Rapid natural gas depletion and the robust chance of gas running out were not addressed in detail. Multifaceted pressures may arise concerning carbon emissions from international and local pressure groups, including foreign buyers, that were not addressed. The model parameters incorporated only the transition and business trends of different kinds of energy resources. Socioeconomic and sociotechnical capacity for the transition were not addressed, which are, according to the policymakers, the most vital drivers in the future transition for Bangladesh (Alo, 2020). These issues are considered in this study's proposed model.

Foreign grants and aid are extremely crucial in giving the renewable transition momentum among the emerging economies where socioeconomic affordability is less (Pattinson, 2012), and technical capacity is poor (Sovacool, 2019). It is very likely for their policymakers to adopt the cheaper but unclean options to ensure energy access to the people first. In a study titled "Renewable Energy, Foreign Direct Investment and Sustainable Development: An Empirical Evidence", the researchers conducted a model of sustainable development to demonstrate the causality and co-integration between FDI (Foreign Direct Investment) inflows and renewable energy consumption, this study considered the data of 43 select countries from 2005 to 2017 and applied panel data analysis. The results reveal a unidirectional causality from renewable energy consumption to FDI inflows and the presence of a long-run relationship. Consequently, the constructed model will assist the government, non-government organisations, and companies in evaluating the significance of renewable energy and FDI inflows in sustainable development. (Parab, et al., 2020). However, Bangladesh, Bangladesh must depend on foreign support to balance the affordability. The proposed model included an expected foreign investment of 5 billion USD (cumulative) over the next decade (Then saturated and terminated) as per the indications from the planning commission of the country (Planning Commission, 2014).

Many studies tried to investigate the main drivers and influencing factors to be considered to understand the transition mechanism and dynamics in a given context (Southwell *et al.*, 2014; Berlo, Wagner and Heenen, 2017; Craig *et al.*, 2020; Khan, 2020). In a study titled "Who Drives the Transition to a Renewable-Energy Economy? Multi-Actor Perspective on Social Innovation" (Park, 2018), the authors examined the many factors and actors that affect the transition to a renewable-energy economy. The authors use a text-mining-based conceptual framework. They then designed a panel data model to empirically examine imbalanced panel data from 25 OECD member nations from 1990 to 2014. Panel vector autoregressive (VAR) models were established initially. The researchers examined complex dynamic interactions between the government, public, markets, and conventional energy industry using a bias-corrected Least Squares Dummy Variable (LSDVC) estimator. Nuclear power, oil, coal, and natural gas provide electricity, along with renewable energy. To determine causal relationships between variables, the researchers performed Wald tests on LSDVC estimator coefficients. This study found that government policies and market mechanisms help the transition to renewable energy, whereas the conventional energy industry hinders it which is also common in Bangladesh (Sarker, 2019). The public does not directly affect the renewable-energy economic shift. This study also shows that government and public involvement in the market helps the transition. All estimations included strong dynamic-path dependence evidence. The study's findings were followed by a discussion of their implications. The findings of this study demonstrate that the shift to renewable energy is facilitated by the active involvement of government and markets, whereas the conventional energy sector exerts a detrimental and direct influence on this change. These results have been used to determine the main actors behind the renewable power transitions in Bangladesh. Government initiatives and foreign grants are the most powerful factors and have some strong correlations.

China has been a pioneer in escalating its renewable generation for two decades (Hung, 2022). Plethora of modelling studies in the Chinese energy transition context are available in the existing knowledge pool (Lin, Wells and Sovacool, 2018; Mamatok *et al.*, 2019; Zedadra *et al.*, 2019; Bai *et al.*, 2020). The paper titled "Analysing the effects of economic development on the Transition to Cleaner Production of China's energy system under uncertainty" (Suo, et al., 2021) creates an ensemble energy system model for China (CN-EES model) by merging a computable general equilibrium model and interval-parameter programming method into a framework for energy system optimisation. The CN-EES model can estimate energy demands under various economic development scenarios, reflecting uncertainties generated from the 2021–2050 long-term planning period and proposing optimal solutions for the transition and management of China's energy system. Findings under numerous scenarios have been obtained and are utilised to disclose the effects of economic development on China's energy system's transition to cleaner output. The principal findings are as follows: (a) fossil fuel (i.e. coal, oil, and gas): would maintain the most influential position in China's energy system, but its share in the total power mix would go down to 61% by 2050; (b) China's energy-supply security would be threatened because the fossil fuel import would exceed the international warning line (CO_2 emission ceiling) in 2041–2045, even if the speed of economic development is slowed down; and (c) renewable power generation will rise consistently. The findings are intended to aid decision-makers in comprehending the consequences of economic development on the transition of China's energy system and in efficiently addressing energy supply challenges, environmental protection, and climate change. A significant paper on the energy transition predisposed to economic development. As China's power demand is rising with its economic escalation, its transition shares similarities with Bangladesh. However, the resources are abundant in China, unlike Bangladesh. Therefore, this thesis must address the gap.

Technoeconomic comparison among different policy options to achieve 100% renewables is another crucial phenomenon that caught the attraction of the researchers (Delucchi and Jacobson, 2011; Mahmud and Town, 2016; Fragkos *et al.*, 2017; Demetriou and Hadjistassou, 2021). To do so, several modelling approaches were used. The paper named "Energy storage against interconnection as a balancing mechanism for a 100% renewable UK electricity grid" (Alexander, et al., 2014) considered two future demand scenarios to illustrate how demand can be met by renewable energy sources and the requirements needed to maintain the security of supply. Several variables were considered, and data were collected to construct the conceptual framework. For example: To form the model, hourly or half-hourly data was collected where possible for electricity demand and supply from RES on the UK electricity network. This study introduced potential renewable energy mixes for the UK that meet the proposed annual electricity demands set out in this study. The estimated capital costs for these scenarios ranged from £200 to £353 billion. However, when considering the hourly demand and generation profiles, the issue of generation variability becomes apparent because of the variable sources such as wind and solar PV. It was found that the level of available dispatchable generation in the UK (hydro, bioenergy and geothermal) in these scenarios is insufficient to meet demand when there is only a small contribution from wind because of high-pressure systems (anticyclones) across the whole of the UK. A range of technological solutions to balance the generation and demand of the UK electricity grid were discussed. It was also determined that a mix of interconnection and energy storage technologies is required to ensure the future highly variable electricity grid is viable. In addition, consumer behaviour towards electricity usage will help reduce the amount of balancing required. However, one of the most crucial factors to the wide-scale renewable electricity grid's viability is the market structure and the governing energy policy. Furthermore, investment in key network upgrades and renewable capacity was found to be required now to safeguard the future electricity grid. This study has many parallel and pertinent ingredients for this incumbent research on the Bangladesh context. This study identifies different renewable energy mixes for the United Kingdom that meet the proposed yearly electricity demands. The incumbent thesis intends to model the sociotechnical capacity to realise the transition, which is a different objective. However, the paper delivers many insights about the probable BaU pathways for the UK context, another contextual difference as the UK is a developed country. Nevertheless, it contains many significant directions for the thesis.

The temporal advancement of the efficiency of renewable power systems is evidentially proven over the last few decades. Many studies endorsed and predicted that the efficiency will rise over time like many other technoeconomic systems (GEA, 2016; Szolucha, 2018; AL-Rasheedi *et al.*, 2020; Enescu *et al.*, 2020). A study named "Energy efficiency and renewable technologies: the way to sustainable energy future" (Abulfotuh, 2007) suggests the effect of renewable power system efficiency may play a colossal role in escalating its generation over time. According to the study, as the efficiency of green power systems rises over time, the generation motivations will also hike worldwide. Due to its direct impacting capacity, the solar power system's yearly efficiency rise has been considered a dependent variable in this incumbent study's capacity modelling.

Various investment mechanisms for renewable promotion have been investigated through several studies that addressed the optimisation of carbon taxation and subsidisation (International Renewable Energy Agency, 2015; Triyanto *et al.*, 2017; Dixit *et al.*, 2018; Lin and Jia, 2018; Hosseini *et al.*, 2020; Jia and Lin, 2020; Sun *et al.*, 2022). Chen et al. (2021) presented a theoretical framework to analyse the effects of cap-and-trade mechanisms on the investment choices of a utility company that operates both a conventional energy source and renewable energy projects. This study examines three distinct cap-and-trade mechanisms: the No cap-and-trade Mechanism (NM), the Grandfathering Mechanism (GM), and the Benchmarking Mechanism (BM). The researchers observe that the utility company demonstrates a higher level of investment in renewable energy when operating under either a Green Management (GM) or a Blue Management (BM) approach, as compared to when operating under a Non-Management (NM) approach. In contrast to GM, the utility company affiliated with BM demonstrates a greater commitment to investing in renewable energy sources, albeit concurrently exhibiting higher levels of carbon emissions. The study additionally demonstrates that the allocation of resources towards renewable energy does not inherently lead to a reduction in carbon emissions. Nevertheless, if the government effectively establishes the carbon quota per unit, BM has the potential to mitigate carbon emissions while simultaneously ensuring that power consumption remains stable. The implementation of a carbon pricing mechanism, such as a carbon tax or cap-and-trade system, might incentivize utility firms to allocate significant investments towards renewable energy sources. Conversely, the adoption of green mandates (GM) can result in the generation of electricity with the least amount of carbon emissions. When a lenient unit carbon quota (or total carbon quota) is set, the utility corporation has the potential to increase profitability by employing a GM or a BM. This study offers novel managerial insights that can inform policymakers. This study provides insights into how carbon taxation may influence renewable power generation growth. It suggests that carbon tax may motivate power and other commodity producers to cut their emissions with some considerable exceptions too. It also gives some innovative ideas on how to approach this aspect. Therefore, the study has a significant emphasis on it to use it in the modelling and to attain other objectives.

Biswas, et al. (2014) examined the mode of subsidisation and its effect on renewable power escalation in Bangladesh. It is found to have a profound impact on the generation and suggests its continuation to increase the incentivisation to a greater extent to harness more success. The subsidy has been included in the modelling as a variable, but it is embedded in the renewable energy budget in the national budgetary allocation and is highly correlated. The subsidy has been included in the model's renewable energy budget to reduce multicollinearity.

Another significant policy option for renewable was found to be the feed-in tariff system. Many studies researched its feasibility and endorsed that as a profitable option (International Renewable Energy Agency, 2015; Gajowniczek and Zabkowski, 2017; Khan *et al.*, 2018; Van Hecke *et al.*, 2018). An analysis of feed-in tariff remuneration models for the implications for renewable energy investment by Couture & Gagnon (2010) discussed A feed-in tariff (FITs) as one of the most effective policy options to encourage renewable energy's rapid and sustained deployment. There exist multiple approaches to formulating a FIT (Feed-in Tariff) policy, each possessing distinct advantages and disadvantages. This study provides a comprehensive examination of seven distinct approaches to organising the compensation framework of a Feed-in Tariff (FIT) policy. These approaches are classified into two overarching categories: those that link remuneration to the prevailing energy price, and those that maintain independence from it. This study explores the merits and drawbacks associated with various FIT models. The discussion culminates in an analysis of these design alternatives, with a specific emphasis on their ramifications for both investors and society. Guidelines and provisions for Net metering were enacted in 2018 in Bangladesh, and several prosumers are already using the incentives from Government on this ground. Government has a projection of 10 GW of renewable capacity within the next 20 years from the rooftops of industrial buildings. This study will use this issue as a point of discussion in the thesis.

The causal correlation between electricity consumption and economic capacity is a common interest among scholars and it has been proved through various studies (Di Sbroiavacca *et al.*, 2014; Bhat *et al.*, 2019; Chilundo, Neves and Mahanjane, 2019). A study titled “Electricity consumption and GDP nexus in Bangladesh: a time series investigation” (Ahamad & Islam, 2011) demonstrates that the coefficients for both short-run and long-run relationships present robust evidence supporting a considerable positive correlation between electricity usage and GDP. The long-term outcomes are resilient when subjected to various metrics and estimators. The findings of the study demonstrate a unidirectional causal relationship, where per capita power consumption has a significant impact on per capita real GDP in the short term. The findings of the study provide compelling evidence of a reciprocal and causative association between per capita electricity consumption and per capita real GDP over an extended period, accounting for feedback effects. It is proposed that the implementation of both energy generation and conservation policies holds the potential to positively impact Bangladesh's economy. The findings are inferred, used, and extended in modelling the incumbent study, and income has been considered a core variable there.

Most of the studies mentioned above have a common feature of the massive inertial effect of system lock-in in the transition landscape (Sai et al., 2015; Trevor et al., 2018; Nelson et al, 2020). The transition still predominately depends on the intentions of multiple stakeholders particularly the policymakers and energy traders (Gupta et al., 2019). In a paper titled “Public Awareness Analysis on Renewable Energy in Malaysia” (Zakaria, et al., 2019), the authors determined public opinions regarding renewable energy and explored the potential barriers against the efforts to find precise ways to explain the benefits of renewable energy. Data was collected throughout Malaysia that included almost all age ranges. This study shows that Malaysian citizens in both urban and rural areas are adequately informed about renewable energy. Even though most respondents prefer to use renewable energy, the price of renewable energy technology is high, reducing its affordability for moderate and low-income families. The government must discuss ways to develop high-quality technology at an affordable price with the relevant ministries and researchers. Thus, people can afford the price of technology, and the government’s goal can be accomplished by 2050. In addition, this study showed that the public’s knowledge of the government’s initiative on renewable energy is low, either due to less exposure or being ignored by the people. However, most people are keen to support the government’s efforts to emphasise the deployment of renewable energy. The finding also suggests that the government should aggressively enhance public awareness through social media as it is easily accessible to people, especially teenagers. As in the incumbent study, public awareness is considered an influential variable in the transition in Bangladesh. This paper has merits in understanding the issue and procedural making of the semi-structured survey/interview questionnaire.

A sociotechnical transition is a set of processes that lead to a fundamental shift in sociotechnical systems (Geels et al., 2017), like energy systems. Such a transition encompasses widespread shifts along different dimensions: technological, material, organisational, functional, institutional, political, economic, and sociocultural. Transitions involve a broad range of actors and typically unfold over the timespan of their influence. During such a transition, new goods, services, business models and organisations emerge, partly supplementing or complementing and partially replacing the current ones. Technological and institutional structures change fundamentally, as well as consumers' perceptions regarding what constitutes a particular service (or technology). Historical examples of sociotechnical transitions include the introduction of pipe-based water supply (Geels and Raven, 2006), the shift from cesspools to sewer systems, the shift from carriages to automobiles (Geels and Raven, 2006), and from land phones to mobile cellular phones (Kenney and Pon, 2011). Considering its salient aspects and issues, sociotechnical transition models seem to have the broadest prospects for deducing pragmatic and intelligible power transition pathways for a developing country like Bangladesh with several indigenous parameters and factors.

2.11.1.1 Transition Models on Bangladesh's Context: A Nexus to the Selection of Methods and Variables

Only four modelling-based studies undertaken on the Bangladesh context of renewable transition were found through a deep online search as of 14/01/2021. Mondal M. A. H. et al. analysed different scenarios from 2010 to 2035 using MARKAL (Mondal, Denich and Mezher, 2014). Different policy scenarios were developed for the analyses of the power sector in that paper. The analyses show that energy imports are needed to satisfy the growing energy demand in the future. However, fossil-fuel power generation can be reduced by having CO_2 reduction targets and/or a fast increase in renewable energy deployment. The authors indicated it would also improve energy security and reduce environmental impacts without raising the cost of energy. They estimated the highest installed capacities of solar PV in Bangladesh in the Null Coal Import scenario of about 41GW, and electricity generation is 84 TWh. The renewables share in total installed capacity in 2035 is predicted to be about 41% of total power demand. The model addressed the 100% renewable potential issues in the most conservative approach considering the current growth rate and mode of green power penetration in Bangladesh, as some studies forecasted the demand for power in 2035 as around 300 TWh (Power Division, 2016). It also used a MARKAL-based tool, a numerical model generally used to conduct an economic analysis of different energy-related systems at the national level to represent its evolution over 40–50 years for a reliable simulation (Zonooz *et al.*, 2009). Nonetheless, Mondal, Denich and Mezher considered only 25 25-year timespan that narrowed down its pertinence, reliability, and applicability. It also focused on the classic resources' transitions based on their business-as-usual trends. This thesis addresses these limitations using a vector autoregressive model (discussed later), including some additional significant variables for the Bangladesh context, including land availability and smart grid expansion. The model considers it a progressively quantifiable variable that will saturate at a ceiling of around 10 GW by 2040. However, green power import has been considered an important variable in the proposed model as multiple agreements, and MoU have been signed with neighbouring countries like India, Bhutan and Nepal for importing hydro, wind and solar power (Shetu, 2018).

Linear optimisation is another familiar tool in the transition modelling arena (Diéguez et al., 2022) which is applicable for the solution of problems where the objective function and their limits appear to be linear functions of the decision variables (Hsiao et al., 2022). A paper titled *Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh* (Gulagi, et al., 2020), analyses energy transition pathways for the case of Bangladesh using the LUT model. This paper uses the LUT (named after Lappeenranta University of Technology) Energy System Transition model, a high spatiotemporal resolution linear optimisation tool, to model an energy system transition from 2015 to 2050 for Bangladesh. Four scenarios aimed at analysing different energy policies were created in order to replicate the present and alternative renewable energy-based policies, with and without greenhouse gas emissions costs. The authors showed that emission costs would accelerate the transition towards a fully renewable energy system. Notwithstanding, cutting these costs down does not significantly affect the energy system. Renewables would still contribute 94% of the electricity generation by 2050. The results indicate that countries like Bangladesh are prone to serious and complicated national risks that lead to several vulnerabilities like high electricity costs, increase in greenhouse gas emissions, energy insecurity and poor political trust if present energy policies are pursued (Gulagi *et al.*, 2020). It suggested that focusing on indigenous renewable resources could help mitigate this vulnerability and bring socioeconomic benefits. This robust study addresses Bangladesh's 100% renewable energy aspirations and prospects, suggesting many realistic policy options. Nonetheless, it focused mainly on the technical and spatiotemporal aspects of solar energy to model the transition pattern with little consideration of the socioeconomic affordability and absorptivity towards the massive green power of Bangladesh, which is very likely to play a vital role in the transition. The incumbent thesis focuses on that.

Another modelling assessment for Bangladesh was undertaken by the Institute of Energy Economics and Financial Analysis in 2016 (IEEFA, 2016). It projected the total electricity demand will be 92.5 TWh by

2024/2025, where renewable energy will have the highest share in electricity production, around 50%, followed by gas at 26% and oil at 12%. Various solar energy technologies will provide 62% of the total renewable electricity. The procedure seems erroneous as nearly 91% of the total electricity generated in 2020 in Bangladesh was sourced from fossil fuels[7], with the major contribution from natural gas (60%) and the remaining from expensive furnace oil and diesel (32%). The installed capacity stood around 21 GW, which includes 2 GW of renewable energy (Sadovskaia *et al.*, 2019). To date, no massively accelerated program from the government or other agencies on greening the power sector can make such a huge changeover within the next five years. The demand assessment here only uses the real-time consumption of electricity by the population, not the affordability or willingness unfulfilled due to transmission incapacity.

Reviewing sectors of the economy as sociotechnical systems involves considering the broader perspective that includes not only natural and built components like energy resources and infrastructures but also societal and institutional elements such as individuals and organisations (Foxon et al., 2010; Geels, 2005; Ottens et al., 2006; Verbong and Geels, 2010). Economic historians have extensively examined shifts in sociotechnical systems. During the late 1980s and early 1990s, researchers at the International Institute for Applied Systems Analysis (IIASA) utilised Kondratiev's notion of extended macroeconomic cycles (Barnett, 2009) and Schumpeter's theories on business cycles (Schumpeter, 1939) to examine innovation and the spread of new technologies (Ayres, 1989; Grübler, 1990; Marchetti, 1988). Extensive historical analyses of previous socio-technical changes in energy systems have provided valuable insights into the broader examination of technological innovation (Fouquet and Pearson, 2006, 1998; Fouquet, 2010; Grübler et al., 1999; Wilson and Grubler, 2011). The topic of "transition studies" is very new and is primarily concerned with normative transitions towards systems that are more ecologically sustainable (Markard et al., 2012). Notable recent examples include the research conducted by Araújo (2014), which examines the significance of transitions research in addressing future "energy mega-trends", and the study conducted by Chappin and van der Lei (2014), which utilises a sociotechnical transitions approach to investigate the literature on the adaptation of energy and transport systems to climate change. However, many of these points are shaped by different patterns and trends in the Bangladeshi context. It is discussed in the next paragraphs.

Why is the progression of sociotechnical or socioeconomic capacity more vital for modelling the transition of Bangladesh to Renewable power rather than the business-as-usual scenario or the carbon emission reduction rationales?

To find the answer to this question, the endemic features of the power sector of Bangladesh are to be explored. Directly or indirectly, 96% of the electrical power comes through direct government initiatives and implementing intervention in Bangladesh (Khondaker, Moazzem and Ali, 2019). The same source confirms that Bangladesh's renewable power proliferation has also been decided upon and driven by state-owned agencies and departments. The foreign aid and grants in the pipeline for renewable power generation in Bangladesh are distributed, managed, and administered by the Bangladesh government. The government also conducts diplomacy to bring such funding (Hossain *et al.*, 2020). The opportunity and capacity to draw in foreign aid for such ventures also depend on the performance and consistency of the government (Parab, Naik and Reddy, 2020). In addition, Bangladesh is still a power-scarce country where 100% access to electricity from the main grid is beyond reach for many people (Power Division, 2016). It also consumes only 615 kWh per annum of electricity per capita, making it one of the world's lowest carbon emitters (considering carbon emission per capita. Therefore, its local contribution to global warming or climate change is negligible and cannot make a strong rationale behind the renewable transformation where atmospheric warming is a global phenomenon (Alo, 2020).

[7]https://powerdivision.gov.bd/site/page/6cd25d49-3150-482a-8bd0-701d18136af7/%E0%A6%8F%E0%A6%95-%E0%A6%A8%E0%A6%9C%E0%A6%B0%E0%A7%87

Recent announcements and statements from the policymakers and stakeholders may be considered to understand the sociopolitical influence on such a transition in Bangladesh. In a power and energy-related conference held in Berlin in 2017, the then Minister of Power from Bangladesh stated that Bangladesh is not responsible for global warming since it is one of the lowest emitters. It is the responsibility of the developed world, which releases the lion's share of the global emissions, to invest in the renewable sector in Bangladesh hence discouraging Bangladesh from picking coal power which is still a cheaper, more reliable and secure option for Bangladesh (Shomoy, 2017). He also added that Bangladesh sincerely intends to escalate its renewable share as much as possible in its economic reach. Still, it cannot take the expensive and erratic green power systems as the major power generation strategy at a massive scale right now when the country is still struggling to provide 100% electricity access to its people with the least amount of power for a standard living (Shomoy, 2017). He also remarked that Bangladesh would accelerate the greening of the power sector following its rise in socioeconomic and technical capacity (Tribune, 2020). The power system masterplans are predominately formulated and implemented by the government in Bangladesh, and according to the policymakers, Bangladesh should amplify its renewable generation keeping pace with its economic capacity. Therefore, Bangladesh's socioeconomic and sociotechnical affordability will likely influence the ultimate renewable power transition.

Some factors, such as land availability or foreign grants and aid, were not found to be considered in any study on Bangladesh's context to date. The land is one of the most crucial factors in generating renewable power as only 0.04915 hectares of land is available per capita in Bangladesh, which is barely sufficient to lead a standard healthy life (Pittaluga and Bank, 2009). Moreover, the population growth is still very high (1.08%), exacerbating the land scarcity challenge (Taheruzzaman and Janik, 2016). Numerical analysis by Bill Nussey shows that a solar or wind farm uses hundreds of times more land than the relatively tiny land footprint of a coal or nuclear plant based on generation/land ratio (Nussey, 2020). Nonetheless, analysis like this often overlooks the much larger footprint of mining coal and uranium. When measured as a snapshot in time, land used for mining coal (0.09 acres per GWh) and uranium (0.06 acres per GWh) uses less land than solar (3 acres per GWh) and wind (26 acres per GWh)(Molina Bacca, Knight and Trifkovic, 2020). According to several studies, solar resources are Bangladesh's most attractive renewable option(Mondal and Denich, 2010; Jacobson *et al.*, 2018). Considering these assessments, solar power still stands atop the socioeconomic efficiency of renewable power generation for Bangladesh. Therefore, the transition models may reasonably consider features like solar power price, solar system efficiency etc., as pivotal variables in the case of designing Bangladesh's transition model.

The technical features of renewable systems and the infrastructural capacity to harness their power at maximum efficiency are also some of the major concerns in Bangladesh's green power visions. If Bangladesh wants to go for mass renewable deployment, the land will become one of the most crucial issues. It is an overpopulated country (1260 people/square kilometre) with intense land scarcity for large-scale PV deployment where solar is the main renewable resource. However, land availability may arise with the shift from agronomy to an industrial and service economy which is already evident (Salam, 2016). Across the coastal belt area, some arable lands are losing fertility due to the rise in salinity caused by the sea-level rise, which may make more land available for this purpose (Mahmuduzzaman *et al.*, 2014). Therefore, the timebound progression in land availability may be used as a dependent variable in modelling the transition and forecasting the future capacity, which is intended to be added in this thesis as a novel approach.

Bangladesh's grid capacity to handle the fluctuating supply from solar power plants is also very poor; it still uses decades-old transmission systems (Maruf *et al.*, 2020a). However, it has made plans to take a smart approach to its grid which is expected to be complete by the next decade (2030). The implementation of such strategies will indeed enhance the technical capacity to absorb the shocks from the power system transition over time. Therefore, these progressive technical enhancements will definitely have sequential impacts on the transition dynamics of Bangladesh from the very beginning of its paradigm shift in its power system.

The price of the energy storage system is another crucial factor in considering a 100% renewable power system, as the supply is intermittent from solar or wind resources. In the case of Bangladesh, the usable daily average solar hour was around 5 hours (Mondal and Denich, 2010). During night and monsoon, energy storage devices like batteries are indispensable, and their price still influences the total consumer end price of consistent renewable power. In the case of grid-tied options like net metering, energy storage may not be essential when renewable is not required to support the baseload (obvious in a 100% renewable scenario). Nonetheless, energy storage is mandatory in realising base-load supply from renewables. The spatiotemporal variability cannot be reduced by only interconnection among the plants. This thesis considered energy storage separately as an independent variable which has shown a consistent reduction in its price in the last twenty years due to its technical advancement (BloombergNEF, 2020).

Foreign grants and aid were vital in Bangladesh's recent renewable power generation rise (Samad *et al.*, 2013a; Alam, Climate and Fellow, 2018). Most of the solar home systems were funded by the World Bank and Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) (Samad *et al.*, 2013a). Bangladesh received $185 Million in World Bank Financing for Renewable Energy in 2019, and more grants and aid are in the pipeline[8]. Considering future carbon trading with high carbon-emitting countries and FDI (foreign direct investment) in the renewable sector may escalate the generation further. By 2030, there is a chance of having a total grant of $5 Billion in the sector (MoF, 2020) that will likely cause a significant addition in the renewable share in the total energy mix. Therefore, this prospect can be used in the model as an independent variable in the case of Bangladesh’s transition context, which was not found to be used in previous models.

Meanwhile, over the last decade, in Bangladesh, unfortunately, these systems did not prove sustainable in nature as the amount of power from such tiny schemes is very small. When the same households became connected to the main grid afterwards, they ceased to use those systems (Tarik-ul-Islam and Ferdousi, 2007). Therefore, for the infrastructural sustainability of such sustainable energy programs, large-scale, long-term interventions are required demanding higher investment and technical capacity than Bangladesh currently has. This study intends to fill that gap by rationalising the proposal for large-scale programs from renewable generation with the escalation in land availability and maximising the use of rooftop spaces.

Suppose the dynamics of such features and variables are quantified, projected, and incorporated into the model. In that case, the simulation will likely produce the achievable transition route Bangladesh can afford and realise. That is why a sociotechnical capacity model is highly pertinent to capturing and presenting the essence of Bangladesh's green power transition pathways.

Research on renewable energy transition and its modelling have primarily focused on the demand-supply driven transformation among countries with high affordability across the world. The models used several different modelling approaches and techniques to determine the parameters to define and determine the model functions using a myriad of variables. The variables were mainly spatiotemporal and technoeconomic categories and they were used as independent influencers on the probable transitions. The transition between developed economies and renewable abundant states is different than that among the resource-scarce states with poor affordability like Bangladesh. Most of the previously done models used highly endemic and situational variables that do not match the Bangladeshi context regarding several issues. Bangladeshi transition cannot be accelerated depending only on the market-driven pull. It requires government initiatives till it reaches a competitively profitable state for all stakeholders. Therefore, modelling Bangladeshi renewable transition needs an essential emphasis to assess its transition capacity influenced by its pertinent sociotechnical variables. The variables must be selected not from a previously done modelling in another country context but analysing the Bangladeshi scenario where policymakers and energy traders play the pivotal role in the transition. If it can be captured with its dynamics propelled by those variables, it

[8] https://www.worldbank.org/en/news/press-release/2019/08/29/bangladesh-receives-185-million-world-bank-financing-for-renewable-energy

would be able to demonstrate the in-hand capacity of the state to ensure a certain amount of green power throughout the spatiotemporal landscape.

Generalised additive models (GAM) have been proved useful and robust in predicting many sociotechnical issues in several different domains like the capacity in health (Han, 2018; Rabideau et al., 2019) and other sociotechnical services like telecom and transport technology transitions (Zachary, 2017) in different contexts. Renewable transitions were not addressed much through this modelling technique. These studies used short time-series data and a wide array of intrinsic and extrinsic variables that match the Bangladeshi renewable transition history. A meta-analysis of transition studies opines that numerous data-driven statistical and machine-learning models have been devised to evaluate the energy transition potential of various locations by leveraging historical data (Matsumoto, 2021). Although the aforementioned methods sometimes yield dependable predictive accuracy (Lourakis et al.,2020), they sometimes lack an in-depth understanding of the associations between factors and their effects on electricity generation and consumption (Khamma, 2020) whereas GAM can often perform better in this issue (Rouben, 2021). One of the main objectives of this research is to deliver that understanding. Furthermore, the importance of model interpretability cannot be overstated in comprehending, regulating, and overseeing the variables that impact electricity generation capacity. The incumbent study wants to perform it too. Consequently, this attribute assumes a critical role and warrants significant emphasis during the modelling process to ensure the attainment of dependable and practical outcomes. Due to these rationales, generalised additive models (GAM) can serve as a versatile, effective, and comprehensible alternative to current methodologies in the modelling and forecasting of renewable energy capacity and demonstrate the dynamic interaction among the variables (Matsumoto, 2021). To obtain the composite model, sophisticated software Matlab uses several solver packages. This study used the Vector Autoregression technique through the Levenberg–Marquardt algorithm to obtain the model.

Since most of the transition modelling studies were conducted on the developed economy contexts, the differences between the emerging economies and them regarding the transition are essential to explore to determine whether the same modelling approaches are to be improvised or not. The next section does it.

2.11.1.2 Differences in transition between developed and developing countries: Why do developing countries like Bangladesh need different modelling approaches?

Analysing the past literature on the renewable transitions in low-income and high-income countries, many noticeable differences were found, which have a profound influence over the transition pathways attributable to the different extent of control of the dominant factors (Dong and Mori, 2017; IRENA, 2017; Nath, Barua and Mohammad, 2019; Maruf *et al.*, 2020a). These differences may also affect the research methodologies for exploring, analysing and modelling the transitions for different geographic, political, and economic scenarios (Elias and Victor, 2005). This section will try to explore, examine and classify those differences to find the knowledge gap addressed in this thesis and to endorse the rationale behind considering different approaches to forecast pathways for Bangladesh's transition.

When analysing a system transition, the current infrastructure and influential factors on the system are to be understood by the policymakers, scholars, and other stakeholders first for deducing the inferences for the future and the extent of significance for each of the drivers responsible for the transition (Ravena, Schota and Berkhoutb, 2012). According to a paper by Rebecca et al., whilst developed states are rapidly switching over to safer and greener technologies from the conventional means of electricity generation, the developing countries are still struggling to introduce merely the least amount of modern energy to their people (Elias and Victor, 2005). Bangladesh is planning its energy policy strategies based on coal-fired power generation for its techno-economic advantages (Alo, 2020). Due to financial incapacity, Bangladesh must wait for renewables to be viable for base load supply. Nonetheless, to absorb the transition shock after two decades, the policymakers must take at least a 'go-slow' approach to gradually prepare the energy sector for the changeover, which has not been well thought out yet. This work proposes to suggest advances in the current strategies.

The starkest feature in the renewable transition in developing countries is the momentum magnitude which is severely weakened by multifaceted factors and parameters like poor affordability, oppressive geopolitics, limited willingness in the local and national government, limited renewable resources and the relatively weaker profit drivers from such green ventures (Tarik-ul-Islam and Ferdousi, 2007). After reviewing several studies and other data sources, some differences are detailed. For simplification, two representatives from those two categories were considered. Bangladesh and Germany were taken as cases for low-income and high-income states.

Table 5 Comparison between the transition features of a developed and a developing country

Feature	Developed states (Germany)	Developing states (Bangladesh)	Remarks
Government Initiatives	Policy, Rules, Regulations, R and D	Policy, Rules, Regulations plus Government Programs funded with public money	The rising importance of environmental issues in the German electorate, initially in the 1970s and 1980s, and legislation such as the 1990 Electricity Feed Law and 2000 Renewable Energy Law played major roles in advancing the deployment of renewable energy technologies (Runci, 2005). In contrast, Bangladesh enunciated its RE policy in 2014 with an extension strategy of only a 10% share of RE in the energy mix excused by economic affordability, poor energy access, poor resource allocation and various other constraints. The government took and funded most of the renewable programs (Power Division, 2016). In Germany, private enterprises take and implement green power initiatives (Balthasar, Schreurs and Varone, 2020).
Foreign aid	Negligible	Major Contribution	Bangladesh's solar home system programs have been majorly aided and funded by the Government of Bangladesh (GoB) and aided by GTZ and World Bank to date(Samad *et al.*, 2013a; Kabir, Kim and Szulejko, 2017).
R&D	Huge investment	No investment	R&D in the EU and USA in the Renewable sector has already exceeded billions of dollars, whereas in low-income countries like Bangladesh, having no notable allocation in such venture depends on free-riding (Mennicken, Janz and Roth, 2016; Power Division, 2016; Taheruzzaman and Janik, 2016; Szolucha, 2018).
Transition Propellers	Market and Supply based, Bottom-up direction	Government initiated and propelled, Top-bottom direction	According to several studies, policymakers, civil society (environment groups), treaties, and agreements significantly drive the renewable transition in high-income countries. In contrast, developing countries often fail to adhere to these options due to lacking capacity.
Electricity access	100% (Main Grid Access)	Main grid access 60%	This remarkable difference between the two contexts endorses the major disparity between their probable transition scenarios. While Bangladesh is still struggling to deliver 100% electricity access from the main grid, barely filling the minimum demand, developing states like Germany have a full-fledged, well-established electricity network providing enough incessant power to all. That is why Bangladesh is first looking for a more feasible option to address the base load demand from more reliable sources like coal power. In contrast, Germany will go renewable from the fossil fuel system. At a certain point in the future, renewable may exceed the fossil fuel share (see: Figure 1 at the end of the table). Nonetheless, Bangladesh may have to select a mixed path where the share will rise over time up to a certain point.
Per Capita Electricity consumption	High[9] (7500 kWh)	Poor (678 kWh)[10]	People and large industries consume electricity in high-income countries in every sphere of life. In Bangladesh, consumption is among the poorest in the world due to poor access and affordability.
Renewable electricity generation shares in the energy mix	Higher	Lower	The share of renewable electricity rose from just 3.4% of gross electricity consumption in 1990 to exceed 10% by 2005 and reached 42.1% of consumption in 2019 in Germany. It is below 10% in Bangladesh[11].

[9] https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?locations=DE

[10]https://powerdivision.gov.bd/site/page/6cd25d49-3150-482a-8bd0-701d18136af7/%E0%A6%8F%E0%A6%95-%E0%A6%A8%E0%A6%9C%E0%A6%B0%E0%A7%87

[11] Burger, Bruno (15 January 2020). Public Net Electricity Generation in Germany 2019 (pdf). ise.fraunhofer.de. Freiburg, Germany: Fraunhofer Institute for Solar Energy Systems ISE. Retrieved 2 February 2020.

Public awareness	High	Poor	Green initiatives are often initiated and pushed to realisation through the mass movements caused by awareness in EU states (Ćetković and Buzogány, 2016). Bangladesh has no notable impact from such masses due to a lack of green awareness and ignorance.
Affordability	High (57,810 PPP USD (2019)[12])	Poor (5,200 PPP USD[13] (2019))	German's per capita income is considerably higher than that of Bangladesh, which profoundly contrasts their transitioning capacity.
Willingness	High	Poor	Highly democratised Germany's people and policymakers have pro-green power mindsets boosted by deeper environmental concerns and higher knowledge on such issues (Zakaria *et al.*, 2019). Some are switching to full green power mode from carbon-emitting power sources. Bangladesh's rural people ceased using solar home systems when connected to the main grid.
Renewable Resources availability	Low to High	Low to High	Germany's average wind power density (primary resource) is high. The turbine tower occupies a small piece of land compared to the power it delivers. Bangladesh's solar power density is also formidable, but the land for solar plants can no longer be used for agriculture. On the contrary, the surrounding land remains usable for other purposes like agriculture even after the wind turbines are erected.
Grid Network	100% Coverage	Below 100%	Germany dispersed and diffused its main grid connection a century ago. Bangladesh has just recently done so up to its subdistrict level. All the households and other premises could not be connected to the main grid supply yet. The rough and hilly terrain, in particular, still misses the grid transmission.
Private initiatives	High	Negligible	Due to lower bankability in the solar power business (strangled by many obstacles, the payback period is more extended in bulk generation), Bangladesh lacks spontaneity from private sector investment. Germany's dense wind potential is more bankable than other emitting options, motivating faster renewable transition.
Large-scale renewable power plants	Many	Few	Germany has many large-scale wind farms with a capacity of more than 100 MWp. Some of these grid-tied farms have as large a capacity as 900 MWp (He Dreiht, 2019; Borkum Riffgrund, 2019). Bangladesh has only one solar plant having more than 100 MWp capacity[14].
Harnessing capacity	High	Poor	Due to the lack of smart grid technology, demand-supply management is not intelligent enough to handle fluctuating supply from renewable plants in Bangladesh. Germany has a much more sophisticated grid capacity to harness the maximum supplied power from its wind plants.
Bulk Transition Rate	Faster	Slower	As a result of its superior sociotechnical capacity, Germany is marching far ahead of Bangladesh regarding its renewable transformation.
Grid stability	High	Low	Highly stable grid technology has been long established and dispersed among most of the developed states of the EU and the USA (Appunn, 2021). Bangladesh's grid stability can barely handle the 10% fluctuation of supply.
Grid capacity to handle fluctuation	Higher	Poor	Smart grids are expanding rapidly in the EU and USA that are well capable of handling variable renewable power supply with better consistency.
Electricity/energy infrastructure (Generation, Distribution, Transmission)	Well established	Underdeveloped and developing	All the EU states and the US have had 100% electricity access from the main grid for many decades, consuming a huge per capita power. In contrast, Bangladesh has only 77% electricity access from the main grid with a meagre consumption rate of 678 kWh/capita.
Power demand	Almost saturated and slowly increasing	Undersaturated and rapidly increasing	The high-income countries like Germany, power demand rises very slowly due to stagnant population size and comparatively slower economic growth rate, whereas in a country like Bangladesh exhibits a rapid rise.
Environmental and Renewable Energy Policy	Strongly enacted and regulated	Weak and Slack Implementation	Renewable energy policy initiatives were initiated long ago among developing states like Germany due to their technological advancements and superiority in research and development. Regarding these aspects, developing states are far behind them. Developed states are likely to formulate their transition policies before developing countries. However, the policies should be formulated differently because of contextual differences. This distinction is addressed in this study.
International and local pressure groups	Strong Influence	Weak Impact	Green politics and eco-socialism are strong in the political sphere of the EU and the USA and have had significant influence over decision-making since the 1980s (Vincent, 2018). In developing countries, environmentalist groups have barely any significant effect on that (Guardian, 2021).

[12] https://datacommons.org/place/country/DEU
[13] https://datacommons.org/place/country/BGD
[14] https://www.tbsnews.net/bangladesh/energy/countrys-largest-solar-power-plant-begins-trial-operation-585014

Power wastage/loss prevention	Highly efficient	High wastage	Many conservation and demand response techniques are widely applied and used in Germany to curb wastage.
Workforce relating to renewable systems	Skilled and efficient	Unskilled and inefficient	Germany is renowned worldwide for its capacity in the realm of science and technology. The legacy is also retained in their workforce relating to renewable technology. Bangladesh is a free-rider in adopting this modern technology with no original contribution. Hence, the human resources of Bangladesh are not yet skilled enough to develop or implement such novel technology at a large scale. Bangladesh depends on foreign experts from manufacturing to transmission and connection at every step.

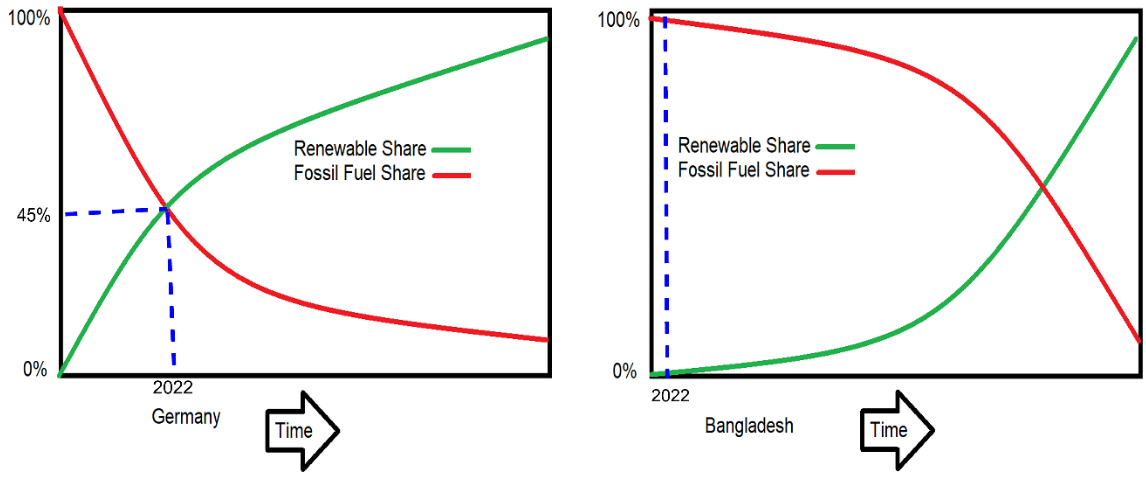

Figure 11 An illustration of the probable transitions in Germany and Bangladesh

The review and analyses of the studies mentioned above on pertinent topics such as renewable power transition in a developing country and the socioeconomic/sociotechnical capacity modelling for such trends have provided the foundation of the incumbent research to address the research gap in socioeconomic capacity modelling in a developing country like Bangladesh domain where resource and affordability both are the pivotal concerns.

The influencing factors over the plausible transition are contextually diverse across the globe depending on market situation, resources availability, technoeconomic capacity, policymaker's and public awareness and intentions, international support and influence etc. (Deorah et al., 2020; Lai & McCulloch, 2016; Zhang et al., 2016). Few authors argued that, in the developing countries like Bangladesh where policymakers strongly control the market, adoption and implementation of green power generation policies are extremely crucial (Ahmed, 2020). The quantifiable variables relating to those factors are enlisted in the Table 8. The review found that the transformation towards renewable power in a developing country is not market-driven but supply-driven, where 100% electrification with sufficient power has not yet been made possible (Biswas, et al., 2014). The recent development of renewable power was initiated entirely by several government programs and projects in Bangladesh aided by multiple foreign agencies (Molla, 2017). It directs this study to consider foreign aid as a primary driving force for transition. Moreover, the contribution and prospects of the rising economic affordability (Ahamad & Islam, 2011), land availability (Edna J.Molina Baccaa & Trifkovic, 2020), subsidisation (Munro & Cairney, 2020), carbon tax (Gulagi, et al., 2020) , green power import (Bhat, et al., 2019) etc. were discussed separately in different papers (Ali, et al., 2011; Baky, et al., 2017;Biswas, et al., 2014;Ali, et al., 2011;Dash & Nakayama, 2019). Some studies opined on the selection of the modelling variables influencing transition (Bolwig, et al., 2018). Solar energy was found to be the most feasible resource to electricity for Bangladesh (Ahmed et al., 2021). Therefore, various technoeconomic factors related to solar like price and efficiency may be considered as variables in the model. If the native resources are found inadequate to meet the local demand, then Bangladesh must consider green power import. Then, it would be another variable in the model as Bangladesh has initiated to import hydropower from neighbouring states. However, filtering all of these articles, the incumbent research strongly felt the necessity of selecting the variables based on the extent of influence in driving the transition, in the case of Bangladesh, which turned out to be mainly the socioeconomic and sociotechnical drivers rather than the sociotechnical system transition trends in developed countries where the green power market is mainly market-driven rather than policy-driven (ALi, et al., 2018). That is why this study will consider the factors like economic growth, renewable energy budget, government subsidisation, foreign aid etc., as the main drivers of the green power transition for Bangladesh. Concerning the selection of the modelling technique, a review of several modelling literatures was conducted, and the generalised additive modelling approach solved through the solving technique of vector autoregression-based logistic modelling was found to be the most rational (Sato, et al., 2014) (Johansen, 2000) with coherence between the findings of those papers and the available data on Bangladesh context. Nevertheless, it incorporates a few studies to analyse the technical particulars like smart grid, interconnection (Alexander, et al., 2014), storage optimisation (Khan, et al., 2020) etc. to formulate recommendations on the future transition. The findings will be used in modelling and analysing the simulation results and to encompass the inferences on the possible transition of Bangladesh during future works.

2.11.1.3 Summary of the notable modelling techniques and approaches reviewed

This table provides a concise overview of the significant modelling techniques and approaches that have been examined.

Table 6 Summary of the notable modelling techniques and approaches reviewed

Name	Limitations
MARKAL	It is a widely used technique to model the transition where it is driven by market-pull and concurrent supply-push. Key limitation: Free market allocation is not available in Bangladeshi context where transition is heavily government centric, and policy driven. The developed states with free market economy and adequate affordability are good options for using this tool to model their transition.
pymedeas	When carbon emission and its social cost are major concerns, this technique is effective to model the transition. Key limitation: GHG emission has very negligible effect on the transition capacity in Bangladesh as it is one of the lowest emitters in the world.
LUT (Linear optimisation)	It focuses mainly on the technical and spatiotemporal aspects of solar energy to model the transition pattern with little consideration of the socioeconomic affordability and absorptivity towards the massive green power of Bangladesh, which is very likely to play a vital role in the transition. Key limitation: Many of the influential variables may not remain linear in future too.
ATLANTIS_India	This model is highly contextualised in Indian perspective where resource constraints were not considered as it has plenty of exploitable solar, wind and hydro potential with negligible land scarcity. Key limitation: Bangladesh has multifaceted scarcities in that domain. It followed the general linear trendlines for the independent variables which is not the case in Bangladeshi context.
MESSAGE-MACRO, Emission Prediction, and Policy Analysis (EPPA) model	The model includes many energy supply technologies and is linked to a climate-land ecosystems model. Key limitation: It has very little pertinence to the Bangladeshi context. It also only emphasised the free demand-supply mechanism which is often absent in developing country contexts like Bangladesh.
Logistic GAM (solved using VAR and L-M algorithm)	GAM can handle multiple number of variables with different types of trends functions together. VAR technique can solve set of multiple equations composed on time series dataset to examine the dynamic relationships that exist between variables that interact with one another. This flexibility can be applied to obtain almost any plausible fit for a forecast. This modelling technique is a very powerful tool to well handle non-linear trends among the independent variables generating plausible fit with commensurate forecasting simulations. It is also quite effective in handling contextual variance through addition of new variables, changing their trend functions and range of searching plausible solutions.
Computable general equilibrium (CGE) model	In this method, the price mechanism reaches market equilibrium where prices can adjust to find an equilibrium between supply and demand. Key limitation: It sharply addresses free-market policy-driven enforcement and does not recognise several exogenous variables which are extremely influential for Bangladesh.
Multicriteria decision analysis (MCDA) coupled with Distributed Energy Resources (DERs) model	It only addresses the interconnection among the resource points and how retail price, microgrids' minimal demand contribution, and available land affect renewable energy initiative design, cost, and distribution. Key limitation: It did not addressed several other impactful sociotechnical factors.

2.11.1.4 Sources of Data for Modelling and Deeper Study

The study needed several data and information to be used while modelling the transition capacity of Bangladesh. Several of them were available with different agencies of the Government of Bangladesh. Since the researcher is an incumbent employee of the Government of Bangladesh, access was given to several data.

Table 7 Data collected for Modelling and Deeper Study with their possible sources.

Data	Use in Modelling	Sources	Justification
Hourly Power Demand Data	To produce an hourly demand profile and to scale up to future demand.	Power Division, Bangladesh Power Development Board, Power Grid Company Bangladesh Limited, Power Cell, Bangladesh Rural Electrification Board, Bangladesh Meteorological Department	The demand profile will be frequently transformed in future due to probable massive changes in consumption rates and trends. The demand projection model considered changing factors like rise in affordability, population growth, industrialization, income growth, promotion of EV cars, weather conditions and other appliances (air conditioning), single scale value nationwide, hourly, 2017, 2018, and 2019 were sourced.
Renewable power availability	Solar and wind energy availability and extractable extent based on suitable sites, hourly/seasonal variability etc.	SREDA, NREL, Power Division, Bangladesh Meteorological Department	Wind and Solar energy maps are already available, along with a considerable number of studies on hourly availability throughout the year. Hourly 2018 weather data is also collected.
Land Availability	Land may be more available with the shifting from agronomy to industrial/service economy, with the salination of coastal belt due to sea level rise etc. Floating solar technology, PV plants on non-arable land and wind firms along coastal belt and offshore may be considered	The income growth projection may have a causal correlation (will be tested); the number of farmers is decreasing, and the yearly data are available from the Bangladesh Bureau of Statistics. The location, area and land class may be obtained from the Ministry of Land.	Essential for large-scale solar PV plants, but the prediction is uncertain.
Economic Affordability	Income Growth projection and its relationship to the purchasing capacity of power and installing large-scale green plants	Vision 2041 (Electoral Manifesto), Ministry of Planning, Power System Master Plan, World Bank economic forecast on Bangladesh	The economic growth projection is itself a complex modelling phenomenon. Nonetheless, some projections are available from WB, ADB etc., and Bangladesh persuasively conforms to those. However, the latest comparative analysis and rational projection will be conducted to forecast the growth.
Grid stability	Bangladesh has launched several projects on enhancing grid capacity and smarting it, and the yearly development milestones are available. It may be incorporated to determine grid stability (variability tolerance capacity). Though it was discussed, since it is correlated to the overall efficiency of the entire system, it is considered embedded in the 'system efficiency' variable.	Power Division, Bangladesh Power Development Board, Power Grid Company Bangladesh Limited, Power Cell, Bangladesh Rural Electrification Board	It may determine the extent of energy storage needed to ensure consistent supply addressing the variable demand. Lack of grid stability will impede the growth of green power.
Public Awareness	People are growing more pro-green power than older people are (Derasid *et al.*, 2021). Therefore, with time, the awareness is more likely to increase and may profoundly impact on greening the power sector.	To interview a representative sample size clustered upon age, roles, and responsibilities to determine the progression of awareness and the relationship to adopting green technology to produce power.	Awareness can influence policy decisions. Therefore, it can push the green power forward. Since it is difficult to establish the numerical relationship, the research did not quantify it for Bangladesh. Nonetheless, it used the interview and survey extracts to check the model's validity and determine optimum policy recommendations.
Renewable Price	To forecast the LCoE of renewable prices	Energy Outlook, Past trends in global, Bangladesh and its	This is one of the major components to be considered to determine the suitable investment periods for Bangladesh while

		neighbourhood countries from various resource and national/global reports	formulating optimum renewable strategies. For example: when the wind power price (LCoE) becomes cheaper than gas or coal, Bangladesh should maximise its effort to adopt wind to the maximum possible extent.
Carbon Tax	The taxation upon carbon-emitting power systems and the products from using such power will accelerate green power promotion.	Bangladesh Planning Commission, Ministry of Foreign Affairs (Climate Change wing)	Carbon taxation and trading may have a complex effect on the transition.
Subsidy	Subsidisation and incentivisation promote green power (Bangladesh have been subsidising the green power sector over the last 15 years)	Tariff Commission, Ministry of Industry, Power Division	There has been a profound effect of subsidy/customs exemption on the rise in renewable use in Bangladesh, which is strongly correlated and can be effectively used in the modelling
Inter-country trading	Amount of Renewable Power Import (Bangladesh is already considering importing hydro and solar power from Neighbours (India, Bhutan, and Nepal) as it has its resource limits)	Ministry of Power, Energy and Mineral Resources (Power Division), Ministry of Foreign	Some agreements are already signed, and Bangladesh is on track to import power of around 10 GW from extra-territory. A major portion will be coming from Green Resources. The amount and tentative timelines are available.
Demand response	The adoption of improved demand-side response can encourage renewable promotion.	Power division, other countries' performances and quantified outcomes, tariffs for business and domestic. Load shedding, irrigation scheduling etc.	Better demand-side response and graduation to different related techniques can maximise renewable power use and ensure the most effective consumption. Therefore, it may be an essential consideration.
Grant/Aid/Foreign Support	There are already foreign grants amounting to half a billion dollars towards the green power sector in Bangladesh. This is more likely to increase, and such projections are available.	Ministry of Finance, Ministry of Foreign Affairs, Power Division	Grant/Aid/Foreign Support has already fundamentally impacted Bangladesh's initialisation and propagation of renewable power. Therefore, it has been considered a significant variable.
Renewable Efficiency	Time-dependent forecasts are available on such progress from various research institutes and studies.	Energy Outlook, NREL	It is an important parameter as Bangladesh has crucial resource constraints, notably land scarcity. Therefore, technology efficiency will profoundly impact the rise in green power use.
Electric vehicles (Cars and boats)	The number of solar boats is rising. The government has enacted solar-powered charging station policies/guidelines. This strategy may positively affect the business of green power from this strategy as there are already one million battery-driven three-wheelers.	Ministry of Power, Sustainable and Renewable Energy Development Authority (SREDA)	As electric vehicles will exert a predominant influence over the power demand shift, it is important to consider it while modelling the future demand profile. The amount of electricity needed to recharge the EVs in the future was projected in this study and it was added to the total demand.
Net metering	Net metering provisions have been enacted already, and the number of prosumers is rising.	Power division (Just PV at present, 1:1 Pricing, Residential and industrial. Chunked pricing data will be collected)	Suppose the large rooftop spaces of the industrial buildings are targeted for installing solar panels; it may add significant power to the energy mix. Net energy metering is a very effective way to escalate the renewable harvest without using expensive energy storage. Through an agreement with the government, several farms have already used the schemes and increased the total renewable yield.
Large-scale green power projects	Large-scale solar and wind power generation programs are being adopted, and projects are being launched	Timelines of the solar and wind projects are available at Power Division	Large-scale solar power plants are being installed all over Bangladesh now. Though Bangladesh is a tiny state with a very high population, policymakers are contemplating and implementing the idea of using infertile lands to generate power. As a result, many new plants are being installed.
The social cost of emission	Since the country's energy policy is biased towards the GHG-emitting system to date, the social cost of carbon emission can be calculated and projected for the carbon-emitting systems.	The timelines for the erection/operation of such plants are available from the Ministry of power and Ministry of Planning and the Power System Master Plans.	Though the social cost of emission is not accounted for yet in Bangladeshi power system master plans, they will be indirectly inserted into the tariffs and carbon taxes shortly. Many reasons behind it are elaborated on in chapters later.

The energy mix for Power generation	Charts show how the power systems are fuelled by different means and resources. The composition of the energy mix varies drastically from country to country and area to region, and it can alter substantially over time.	The energy mix curves are available for the last five years daily from the Power Division	Historical, economic, social, demographic, environmental, and geopolitical considerations often influence policy decisions in the energy mix. This thesis considers energy mix as an outcome of different causing reasons, not an input variable. Hence, it was not intrinsically used as a variable in the model.

2.11.1.5 Conceptual Framework for the Modelling

The conceptual framework provides a cohesive overview of the influential factors and the building blocks for simulations of evolving energy infrastructure systems. It presents the choices modellers need to make and the applicable restrictions (Chappin & Gerard, 2010). Thus, it aids in balancing model development of evolving energy infrastructures, foreseeing the future of the systems and domains, and enhancing the capacity to design policy with desired implementation outcomes. In addition, the framework serves as a typology of transition models: it characterises existing and new models in terms of their ability to trace specific interventions – and provides input to assess the viability of transition management. Consequently, the modelling framework structures the discourse on transitions (Köhler, et al., 2019). Renewable transition in the energy sector is one of the most thought-provoking events worldwide, triggered by global climate change issues. Unfortunately, though it is indispensable to cut down the carbon emission from the power generation systems around the world, the socioeconomic system inertia in the energy use domain of current civilisation, the progress is still too slower compared to the requirement.

Nonetheless, the recent development in greening energy sources shows some remarkable escalation regarding its technological and economic efficiency, R&D initiatives and successes, renewable share in the energy mixes, mounting investment, penetration and proliferation of the green power systems, awareness and awareness and acceptance, policy adoption and implementations etc. These developments denote the massive renewable transformations and reforms worldwide soon, making it a prime concern for policymakers and stakeholders. Realising its inevitable prospects and unavoidable transitioned future, the Parliamentary Standing Committee for Energy, Power, and Mineral Resources of Bangladesh has recommended a study and an action plan to move towards 100% green energy by 2050 (Alo, 2020).

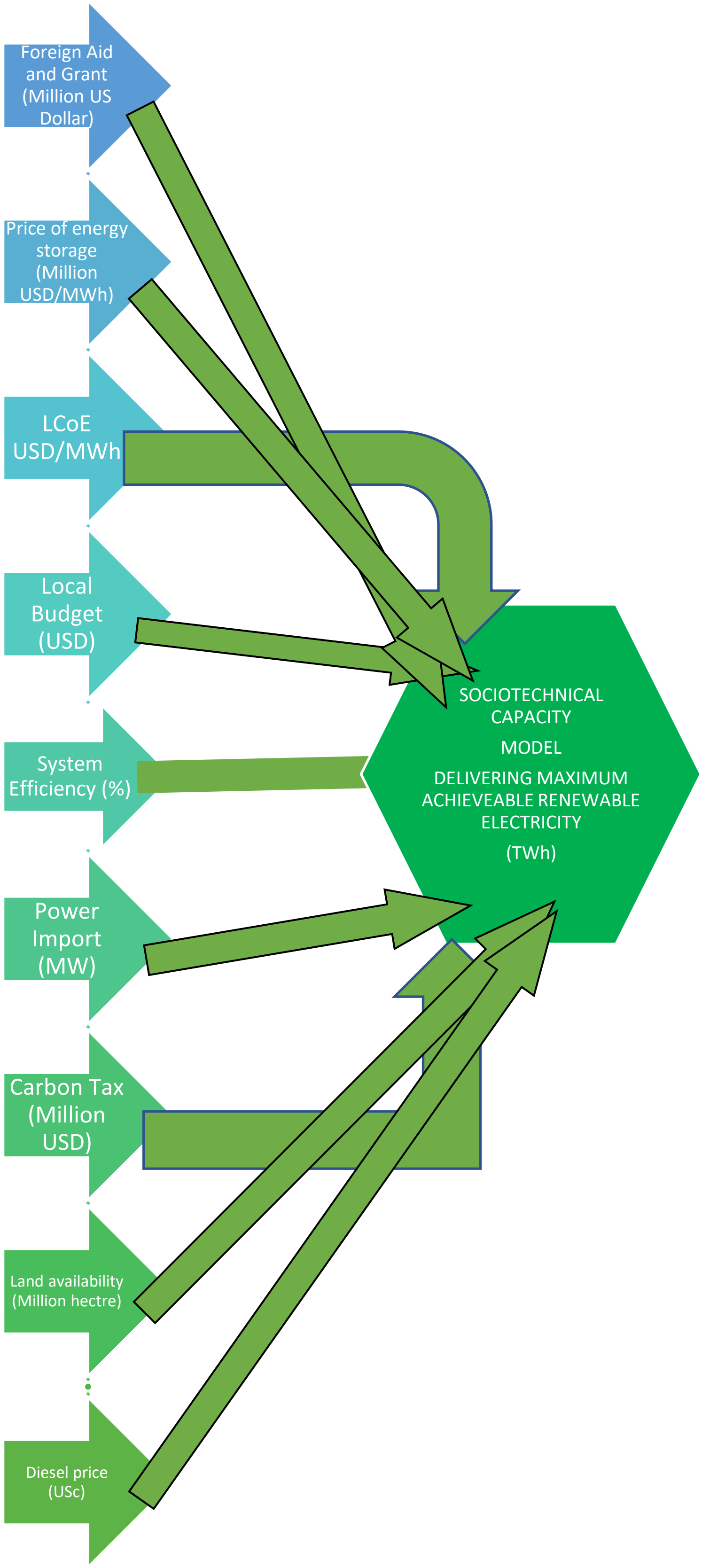

Figure 12 Model inputs and output (Entity-relationship (ER) Diagram of the Sociotechnical Capacity Modelling for Green Power Transition in Bangladesh)

This study endeavours to construct an expressive model for the Renewable transition in Bangladesh in the Power sector based on some influential variables and future energy demand. It elaborates on the framework for developing the simulation model of transitions in energy systems. Before that is done, the requirements for the modelling framework and the simulations that stem from the analysis will be discussed. Possible modelling paradigms are discussed, and a non-linear regression based ''Sociotechnical Capacity for transition' Modelling as an archetype is intended to be approved. Subsequently, a typology for categorising models to trace specific interventions would be chosen.

The current government of Bangladesh has made a visionary aspiration for the transition by 2050 and is now preparing the roadmap (Alo, 2019). Based on the past trends and rationales, the following assumptions were made regarding the probability of transition in Bangladesh perspective:

1) The renewable share may rise with the **economy's size growth** (E). It was endorsed in several literatures before in many different settings (Masuduzzaman, 2011; Pirlogea, 2012). This type of rise or transformation rate will be regressed and extrapolated considering the past and current trends and other learning curves available.
2) The renewable share may rise with the **price** (**P_{fossil}**) of fossil-fueled power. It is highly likely that if the renewable power becomes competitive with the rise of fossil-fueled electricity, investors move in favor of green systems (RenewEconomy, 2023).
3) The renewable share may rise with the escalation of such technology's technical efficiency (ηR), which refers to the part of energy in the form of irradiance that can be transformed via photovoltaics into electricity by the solar modules. The efficiency-generation nexus was validated by a wide range of literature. With the escalation of technoeconomic efficiency of solar modules and wind turbines, green power generation rose accordingly (IRENA, 2019).
4) The renewable share may rise with the **government's subsidisation (S)/incentivisation of such businesses**. (Direct Policy Intervention) (Sun *et al.*, 2022).
5) The renewable share may rise with the public interests built from green **Awareness (A)** (Zakaria *et al.*, 2019) .
6) The renewable share may rise/fall with **foreign** investments, grants, aids, donations (**F**) etc (WB, 2018).
7) The renewable share may rise with foreign buyers' exposure to **Carbon tax (C)** on export items. Indirectly, there may be embargos from the buyers on carbon-emitting products (ProthomAlo, 2019).
8) The renewable share may rise with the renewable power **Import** (**I**) from neighbouring countries (WE, 2017).
9) The renewable share may rise with the decrease in **Energy Storage Systems (ESS)** price (Li *et al.*, 2022).
10) The renewable share may rise with increased **Land availability (L)** (Star, 2020)**.**
11) The renewable share may rise with the expansion of **Net Metering (N)** (NRDE, 2021)**.**
12) The renewable share may rise with the **Smart Grid (G)** adoption and extension (IEEE, 2019).
13) Miscellaneous (**M**). (The number of variables may increase/decrease as per contextual necessity). It has to be considered in the model if the aforementioned variables cannot suffice to deliver a good fit. It may turn into a modelling need and it would denote that the chosen variables are not sufficient to deliver a good fit on a particular modelling function (Cortina, 1993).

Therefore, preliminarily, the renewable share (R) in the total electricity generation may be formulated as a function of the variables mentioned above:

$$R=f\,(E, P_{fossil}, \eta_R, S, A, F, C, I, M, N, G, L, ESS) \quad \text{(Equation 1)}$$

All the factors are time functions and can be functionalized through time-series data regressions. For example:

$$\mathbf{E_t}= E(1+r)^t, \quad \text{(Equation 2)}$$

Where E_t=Size of the economy at t^{th} year, E= Initial size, r= Projected annual growth rate. Initially, the stages of growth will be followed by Rostow's model in this research, which may be modified according to the best-fitted models upon revealing closer relevance (Hossain, 2016). For simplification, this research will take Bangladesh's projected per capita income in 2041 as a developed state now (12000 US$) and adjust the inflation over time (WB, 2019).

Similarly, $\mathbf{P_{fossil}}$ may be expressed as an exponential equation like

$$\mathbf{P_{fossil}}=ke^{mt} \quad \text{(Equation 3)},$$

Where **t** is the number of years, and k and m are constant coefficients), which may be regressed from various learning curves or reliable energy price forecasts.

These generalised expressions will become more rationalised by considering various influential factors and be adjusted for practicality. Similarly, other expressions will be regressed/extrapolated from past trends and forecasted for the modelling.

Thus, combining all of them, R becomes a time function.

$$R=f\,(t) \quad \text{(Equation 4)}$$

This function can be used to determine the optimum transformation at any instance. The optimal decisions may be acquired by solving differential equations with appropriate boundary conditions. Like, at time t, for *the maximum possible generation*, the rate of transformation,

$$\frac{dR}{dt} = f'(t) = 0 \quad \text{(Equation 5)}$$

When the maxima occur, the time of occurrence can be derived using this condition. Vice versa, if a time is given for the maximum possible amount, it can be determined at that time. The obtained model can be simulated for various shock analyses and based on the intensity of impacts, can be used for policy and strategy formulations and determination of main challenges. Suitable software like R or MATLAB will develop the model and run the simulations. Each regressive analysis will consider risk factors and uncertainties to measure the range variation of policy strategies.

The proposed model has several different aspects. It is an integrated simulation model to determine the maximum possible renewable power generation based on the sociotechnical capacity of Bangladesh at a certain point in time. It incorporates multiple mathematical operations while constructing the model function.

Firstly, it is a nonlinear function because the recent trend of power generation in Bangladesh exhibited a rapid rise which is nonlinear compared to the past. Speeding it up is required to address the accelerating power demand due to rapid industrialisation and economic growth. Electrical generation capacity has increased from about 5 GW in 2009 to around 25 GW in 2023, and access to electricity has expanded to nearly 100% of the population (GoB, 2023). Compared to the previous phase (1971-2010), this growth is nonlinear and nearly exponential[15]. The model function to deduce the amount of renewable power based on Bangladesh's sociotechnical capacity may be expressed as:

$$R=f\,(\mathbf{E, P_{fossil}, \eta_R, D, S, A, P_c, F, C, G, L_A, N_m, E_{SS}, B, R_s, I, P_b, C_e, M}) \quad \text{(Equation 6)}$$

where R=Renewable Power Generation in TWh, E=Economy Size, $\mathbf{P_{fossil}}$ = Price of the Fossil Fuelled Power, D=Power Demand, S= Subsidy, A= Public Awareness, P_c= Social Cost of Carbon, F= Foreign

[15] http://old.sreda.gov.bd/files/Draft%20Final%20Report%20-%20National%20Solar%20Energy%20Action%20Plan,%202021-2041.pdf

Aid, C= Carbon Tax, G= Grant, L_A =Land Availability, N_m= Net metering, E_{SS}=Price of storage, B=renewable Budget, I= Foreign Investment, M= Miscellaneous etc.

Reforming it into a classic logistic equation extended for a GAM or Generalised Additive Model (as Power demand growth generally follows a logistic trend (Harris *et al.*, 2018))

$$f(X) = \frac{L}{1 - B * e^{-\{f_0 + k_j \sum_{j=1}^{p} f_j(x_{ij})\}}} \quad \text{(Equation 7)}$$

(Here, f(X) is the dependent variable function depending on independent x, L is the upper limit of the growth or the saturation point, and)

Reforming it for power generation as the dependent variable gives,

⇨ $R = A/(1+e^{\{k_1 f(E) + k_2 f(P_{fossil}) + k_3 f(\eta R) + k_4 f(D) + ... + ... + ... + ... + ...\}})$ (Equation 8)

- All the variable functions are a function of time or year. Hence, E= f_1(t), η_R = f_2(t), D = f_3(t), S= f_4(t), G= f_5(t), B= f_6(t), ESS= f_7(t), L= f_8(t), C= f_9(t) etc.

⇨ $$R = \frac{A}{1 - B * e^{(\{k_1 f_1(t) + k_2 f_2(t) + k_3 f_3(t) + k_4 f_4(t) + k_5 f_5(t) + k_6 f_6(t) + k_7 f_7(t) + k_8 f_8(t) + k_9 f_9(t)\})}} \quad \text{(Equation 9)}$$

- All variable functions are fitted to the suitable curves (functions f_1, f_2, f_3........f_9) using the curve fitting tool in Matlab applying rational boundary conditions.
- All regression coefficients (ks) are determined in MatLab through a non-linear Vector Autoregression solution technique. Then ten years' values of each variable are inserted in the above equation. However, since this is a non-linear model, these 'k' values do not denote the precise weightage or potency of the corresponding variable. The variables are also of different types and are uncorrelated.
- The values of `K`s are determined by fitting the curve in MatLab (Using the Levenberg-Marquardt and Trust Region Algorithms, detailed later)
- R_{total} was fitted to a logistic curve saturating at the maximum demand projected in the research (For example, 400 TWh).
- The R_{total} was simulated for varying the values of any or multiple variables.
- R_{total} was plotted against time to observe the transition trends from Equation 9.

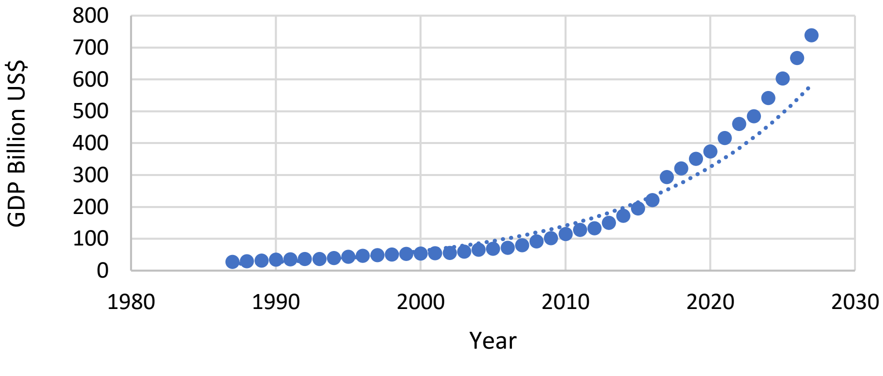

Figure 13 Year-wise GDP growth trend of Bangladesh, past and projection (World Bank, 2020)

- The caused change in the Transition of R_{total} can be observed by varying the variable functions. Secondly, the power demand rise along with the economic development in a country with consistent growth is generally a logistic function[16] where the demand would saturate over time following the logistic growth trend of the population (Kwasnicki, 2013a).

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[16] https://www.resilience.org/stories/2009-04-20/peak-people-interrelationship-between-population-growth-and-energy-resources/

This trend was found to be used in several modelling efforts where the classic logistic regression function was used (Bodger and Tay, 1987; Kwasnicki, 2013b; Kucharavy and De Guio, 2015; Zedadra *et al.*, 2019). Logistic analysis has shown a surprising capacity to process historical data in that the information relevant to the evolutionary behaviour of energy systems is contained in a very restricted time series (Kucharavy and De Guio, 2015). Bangladesh's renewable power generation has seen the first significant rise in the last ten years, and before that, production was stagnant for decades (Gulagi *et al.*, 2020b). Therefore, the base data to model the transition is a short-period time series. Despite being short, it may be a significant period for applying a suitable modelling technique, such as a logistic one, when that period significantly impacts the subjective domain (Bodger and Tay, 1987). In the recent past, some rapid transitions like non-smart mobile handsets to smartphones took a very short period, like a decade, for a significantly higher rate of transformation (Cecere, Corrocher and Battaglia, 2015; Gadzama, Joseph and State, 2019). This issue endorses the rationale behind considering a short time series for modelling in particular cases when the transition rate is significantly higher (Bai, 2000; Mamatok *et al.*, 2019). This rapid growth phase provides a sound basis for predicting the future power generation capacity of a developing country like Bangladesh. However, certain precautions should be taken, or at least kept in mind when using the results. In a moderately consistent socioeconomic domain, the main contributing factors to the future power demand, namely, population, economic growth, and aggregated magnitude of power consumption by electrical appliances, often exhibit classic logistic growth patterns over time (Kwasnicki, 2013b; Kucharavy and De Guio, 2015; Harper *et al.*, 2019). Therefore, retaining consistency in the socioeconomic indices, Bangladesh would prefer an optimum transition pathway for implementing a 100% renewable power system based on its progressive sociotechnical and socioeconomic capacity. The probable escalation trend will likely be a Sigmoid Curve based on a logistic function (Kwasnicki, 2013a). Another basis is found in the available literature for the prospective future changeover being a logistic trend. Renewable models to keep the global temperature rise under 2^0 Celsius demand fast-tracking transformation dynamics enacted immediately (McLeman, 2018). However, Bangladesh is not a prominent actor in climate change crimes but is potentially one of the worst victims of it. Therefore, the global green energy movements may support the greening of its power sector.

2.11.1.6 Deciding over the variables and patterns of variables' projections

Wright's Law enunciates that ''for most technologies, every doubling of cumulative size of the production will lead to a set percentage drop in the cost of the technology'' (Eden, Williams and Ackermann, 1998). It happens through learning by doing, a blend of innovation that improves the technology itself and innovation that decreases the amount of labour, time, energy, and raw materials needed to produce the technology. Wright originally noted that every doubling of scale led to a consistent percentage reduction in cost in 1936 when investigating the production costs of aeroplanes. Following Wright's first observation, a similar power law relationship between cumulative production and cost has been established in other fields. For example, every doubling of cumulative Ford Model T output resulted in a roughly 16% drop in cost per unit (Eyre *et al.*, 2018).

Some socioeconomic/sociotechnical indices show a plausible pattern that can be incorporated into the modelling. Considering the learning curves of establishing and operating wind and solar plants, the price of installed wind power has decreased by 70% over the past decade, while the price of installed solar power has decreased by 89% (Figure 18). Thus, the prediction precision of Wright's Law is also demonstrated in renewable technology. Later, Swanson's law the observation that the cost of solar photovoltaic modules tends to decrease by 20% with every doubling of cumulative volume shipped. Every ten years, costs fall by 75% at the current rate. A similar trend is found in the case of lithium-ion battery packs, too (Figure 14). Therefore, the incumbent model significantly stressed adjusting to the latest trends in learning curves to attain its objectives.

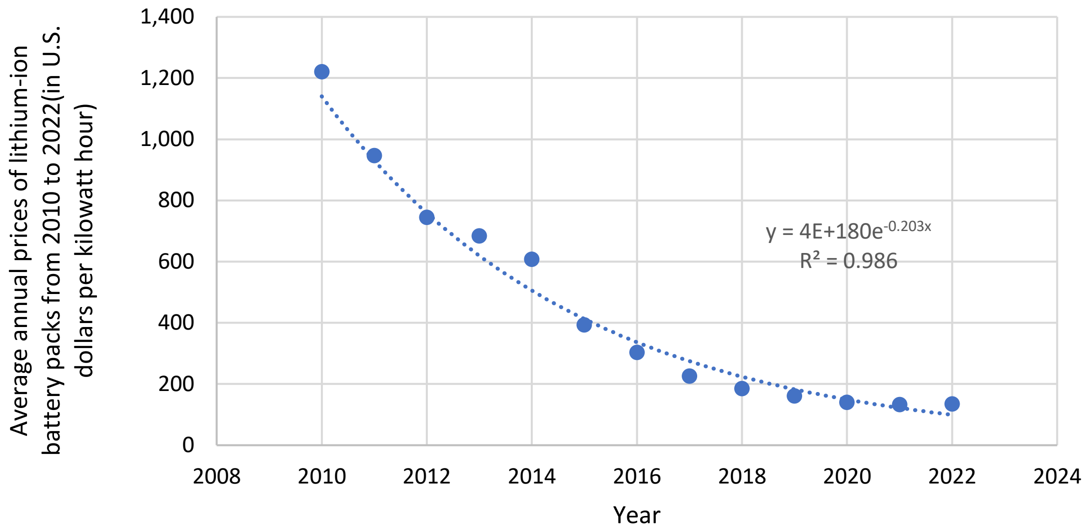


Figure 14 Average annual prices of lithium-ion battery packs from 2010 to 2022 (in U.S. dollars per kilowatt hour)

Learning curves of the model variables and other trends are used to construct and enhance understanding and insights into the transition dynamics by extrapolating them. Their future pathways can be constructed and simulated with varying influential factors that are already predictable significantly due to past insights, experiences, and contextual rationales. For example: If the renewable energy budget increases over time by the trending curve B= 2.65t+35 (t=number of years from the first year of consideration, B=budget in a million dollars), we can use this curve to generate a future scenario and incorporate it in the model. However, we know from past studies and experiences this kind of budgetary allocation in the government's annual budget gets diminished over time as the private agencies are likely to get involved in the sector due to the privatisation progression in a progressive democratic country with a rising free-market economy like Bangladesh. That is why we can set a threshold to this allocation by modifying the function to a logistic (Sigmoid) one where there will be a maximum saturation limit. Similarly, the model may incorporate smart grid expansion and public awareness in the business. The goodness of the fits would be ensured through the use of various measures like R-square.

If the smart grid expansion is already embedded in the system efficiency progression as it rationally causes augmentation in the total system output, it will be discarded. In these ways, the modelling will be judiciously amended based on past experiences and current contextual rationalities for more reasonable simulation outcomes. However, since grid stability is crucial in handling fluctuating renewable power, the thesis will focus on it separately.

The causal diagram displays causal relationships between variables in the causal model of socioeconomic capacity to drive the green power transition in Bangladesh. This causal diagram includes a set of variables (or nodes). An arrow connects each node to one or more other nodes upon which it has a causal influence. In this diagram, a red or green arrowhead delineates the direction of causality, e.g., an arrow connecting variables A and B with the arrowhead at B indicates that a change in A causes a change in B (with an associated probability). A path traverses the graph between two nodes following causal arrows.

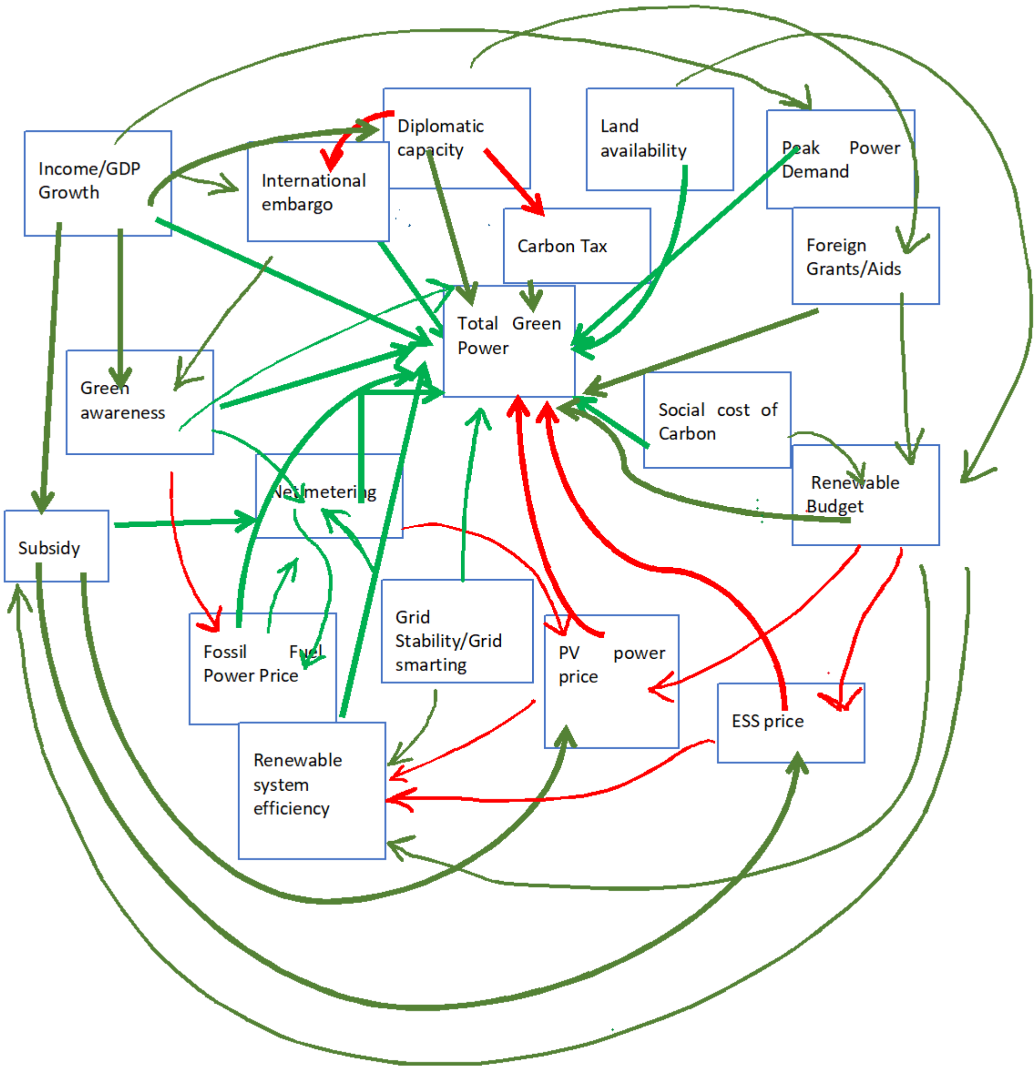


Figure 15 Causal relationship among the influential variables over the transition

In this diagram, the green Arrow denotes reinforcement, red arrow denotes the reverse loop. For example, if the ESS (Energy storage system) price goes up, total green power or renewable system efficiency will be regressed; if Subsidy is raised, the ESS price may fall. It gives a simple understanding of causality among the variables and the probability for the consideration of them to be used as a dependent or independent variable. It may provide the suggestion of removal of variables upon correlation to make the model robust. It has been discussed more elaborately in Table 8. For example: from the notions of this diagram, the subsidy was embedded in the renewable power budget and was safely discarded from direct consideration. An equivalent scenario occurs in the Bangladeshi context (Planning Commission, 2020). The interrelation among them and their nature are already detailed in Table 8. It also gives the idea of how they were combined and segregated.

The following table enlists the influential variables and factors supposed to Make an Impact on green power transition in Bangladesh. It also explains the rationales behind the final selections of the variables for the modelling.

Table 8 Influential variables and factors supposed to Make an Impact on green power transition in Bangladesh.

Variables	Remarks
Time (Year)	The timeline is limited to ten years as the escalation in renewable power began in 2010 in Bangladesh. The plans for green power generation also predict exponential growth compared to the recent past, which is supposed to saturate over time, keeping pace with the development in influential socioeconomic capacities. It is inferred that the income growth will escalate the affordability to generate green energy. The renewable share may rise with the growth in the size of the economy (E). This rate of rise or transformation will be regressed and extrapolated considering the past and current trends and other learning curves available. Bangladesh's primary renewable power resource before 2010 was the only hydroelectric power plant at Kaptai which has been running since 1961, saturating the hydro capacity of the flatland country. After 2010, aided by several foreign agencies, solar power (through micro solar home systems) started to emerge in a true sense and escalated the cumulative growth of renewable power in Bangladesh. Though this growth is supposed to be a logistic one, up to 2050, it'll keep rising steadily, and then it'll start to be horizontal, following the classic logistic trend. That is why this model considers 2010 as the starting point of consideration. Since the incumbent study focuses on renewable targets by 2040 and beyond, consideration is limited by the recent past and 2050. However, we assumed the demand would saturate by that point, and we extrapolated the model up to 2100.
Income per capita (US$)	The Trend is considered here, logistic as general economic growth for a growing population inside a country follows a logistic pattern (Kwasnicki, n.d.). The rationale for selecting it was elaborated in the literature review section. Consistent income/GDP growth in a country not only enhances the affordability to adopt new technology in a country but also endorses its credibility to the foreign partners regarding their investment guarantee with satisfactory rate of return.
Fossil Fueled power Consumer End Price (Cents, Normalised 2018 value) (Diesel/Litre)	The renewable share may rise with the hike in the Price (P_{fossil}) of fossil-fuel power. The impact of subsidy on fossil fuel (Diesel, Octane, LNG, and Petrol) are neutralised at the user end electricity price, which is raised accordingly for the compensation. The study considered the consumer end price of diesel. Diesel has been taken as an example of fossil fuel here as its use is rising with the incremental installation of diesel-peaking power plants all over the country to tackle the rapid power demand hike. These plants are easy to operate and take comparatively less installation time, which is crucial to establishing an emergency power supply. At present, more than 67% of the peak demand and 10% of the total power demand are met by Bangladesh's diesel-peaking power plants, and the numbers are still rising. Solar-powered irrigation pumps in Bangladesh rapidly replace diesel irrigation pumps to reduce costs. From the global trends, it may be rationally inferred that the hike in diesel price (consumer end price) consistently encouraged the installation of solar power generation. The price of other fuel rose similarly. This model is considered Diesel's price due to its rampant and rapid adoption in quick rental power generation schemes adopted by the government.
System Efficiency η_R (%)	The renewable share may rise with the escalation of such technology's technical efficiency (η_R). In the 21st century, efficiency continues to rise, and the future forecast shows no signs that efficiency will stop increasing. In addition, the cost of solar power (Bangladesh's main green energy source) has been decreasing. Therefore, the rise in solar capacity and the willingness to buy solar power will increase with the increasing efficiency of solar power systems. Unfortunately, Bangladesh has suffered from poor quality control and regulations regarding low-quality solar panels' poor efficiency for decades. While other countries often use panels with an efficiency of ~15%, the panels used in Bangladesh are frequently found to have up to only 11~12% of electricity generation efficiency (Islam, 2019). Hopefully, these substandard panels are being replaced with better ones recently as the government enacted strict regulatory terms and conditions. In this consideration, time laps are limited as the higher efficient systems are not installed every year of development. However, to keep it simple, the model was done considering the normal progression mode in technical advancement. The trend considered 1% efficiency rise/year saturating to a maximum 50%.
PV price (monocrystalline) ,LCoE of Solar (USD/MWh)	The price of PV systems drastically fell in the past decade from 280 USD/MWh to 50 USD/MWh (IRENA, 2021). It followed an exponential fall. However, rationally it cannot go below 0. Therefore, the model put a threshold saturation of 10 considering the minimal manufacturing costs (IENE, 2020).
Peak Demand (MW) (in a year, half hourly average basis)	Demand is rapidly rising in Bangladesh as the economy and population are growing. Since they are directly correlated, the model will consider only the economy (GDP per capita) to capture and embed the combined effect of the driving factors in the demand forecast model. It has been detailed in demand forecast section.
Per Capita Electricity consumption (KWh)	Per Capita Electricity consumption (kWh) is directly related to the population's demand and power consumption, which is also embedded in the per capita income rise and population growth rates. Therefore, a model will be formulated to forecast the future demand and the estimation will be used in the transition capacity modelling.
Green Awareness/Political Commitment	Developed states are often nudged by the green movements that compel them to adopt green initiatives. In contrast, in Bangladesh, this is not yet a considerable factor behind the green escalation due to the lack of green awareness and affordability. Moreover, the concern is reflected in the renewable power budget in the national budgetary scheme anyway. That provides a robust and rational ground for subtracting it from the model variable list.
Cumulative Aids, Grants (mUS$)	It has been one of Bangladesh's most powerful green transition drivers, as most green power projects were funded and propelled by foreign donors and partners. However, as per the future funding prospects, the foreign grants will be reduced after 2030, so Bangladesh has to be on its own. That is why a predicted cumulative grant of 5 billion USD has been set as the desired saturation point in this modelling (Ministry of Finance, Bangladesh, 2019).
Carbon Tax (mUS$)	Recently at a trade conference, Bangladesh was warned about escalating its coal power production and was at risk of an embargo with high taxing against the products produced with carboned power like coal. This kind of foreign pressure may push Bangladesh towards greening its energy sector. However, the internal framework of such impositions is still under construction.
Green Power Import	Bangladesh intends to connect to the regional grids when constructed to bring green power in. Since the country lacks lands for solar, potent wind or hydro, it proposes installing green plants in other states with its fund and bringing the power in. Bangladesh is already on the verge of contracting with Bhutan and India for such a venture. There are some

Variables	Remarks
	diplomatic bargains, but hopefully will be settled down shortly. Bangladesh wants to bring 4000 MW of green power by 2030 (PDB,2018). It expects to bring more with the development of regional power grid in future, too (MoFA, 2020).
Renewable Budget (mUS$)	According to an extensive study by the Ministry of Planning, Bangladesh, the additional investments between 80 billion USD and 120 billion USD by 2050 must transition towards a 100% green power system (CPD, 2019). This model considers 100 billion USD at a normalized rate of 2018 and fits the trend in a logistic curve. Renewable subsidisation and incentivisation are allocated in the national annual budget for various power generation projects. Further incentives from foreign loans are also allocated in this manner. It seems a very influential variable in the transition that has a direct impact. It is discussed more elaborately in the next chapters.
Net Metering (MWp)	Bangladesh has severe land scarcity due to high population density and has little scope for installing large-scale renewable power plants. Therefore, net metering seems a timely and effective technique to enhance this country's green power generation prospects by tackling the major challenge of land unavailability. Being a developing country and a global leader in producing certain commodities like garments, Bangladesh has many medium to large production plants/mills/factories across its landscape, occupying a significant portion of its available land. A study by the researcher found that the estimated total extractable solar power from such premises is around 5 GWp with a corresponding annual power of 7.5 TWh, which could contribute more than 6% of Bangladesh's current consumption. It may be considered a strong proponent towards green power. However, it has been considered embedded in the renewable power system's efficiency rise as it increases the total feed-in proportionately.
Smart grid transmission (km)	Smart Grid Transmission has not been initiated yet but will soon occur. Bangladesh has launched several projects on enhancing and smartening grid capacity, and the yearly development milestones are available. To avoid uncertainty and due to lack of available data, this model is not considering it yet as an independent variable. *It is assumed that it is embedded in overall system efficiency.*
Land Availability (mH)	Land may be more available with the shifting from agricultural to industrial/service economy, with the salination of the coastal belt due to sea level rise etc. Floating solar technology, PV plants on non-arable land and wind firms along the coastal belt and offshore may be considered. The income growth projection may have a causal correlation, the number of farmers is decreasing, and the yearly data are available from the Bangladesh Bureau of Statistics.
Social Cost of Carbon (% loss in GDP)	The social cost of carbon is an estimate of the economic costs, or damages, associated with emitting one more ton of carbon dioxide into the atmosphere and, consequently, the compensation for reducing emissions. It is the marginal cost of the damages generated by emitting one additional ton of greenhouse gases (equal to carbon dioxide) at any given moment, including "non-market" repercussions on the environment and human health. Considering a type of market failure, the social cost of carbon is a calculation centered around implementing remedial steps against climate change. Putting a price on a ton of released CO_2 is intended to assist policymakers and other legislators in determining if a policy designed to mitigate climate change is justified. Since Bangladesh is still one of the lowest carbon emitters, policymakers have not yet considered the social cost of carbon. However, it may be entrenched into other schemes like rehabilitating the climate refugees through climate change adaptation programs, which foreign donors still support. *Therefore, the social cost of carbon is considered embedded in the foreign grants and aid in this model*.
ESS (Energy Storage System) Price USD/kWh	To ensure a reliable power supply from renewable sources like solar or wind, ESS is essential, which still makes the whole system expensive. Fortunately, with the technical advancement through R&D, the price of batteries is decreasing dramatically. It is a vital factor in green motivation. It is a variable in the transition model.
Subsidy (US$)%	There has been a profound effect of subsidy/customs exemption on the rise in renewable use in Bangladesh, which is strongly correlated and can be effectively used in the modelling. Still, it is entirely included in the renewable budget. *Nevertheless, it is embedded in the renewable budget and hence is opted out as a variable in the model function.*
Renewable Power (TWh)	It is the resultant outcome of all the independent variables considered in the model function.

Only the Highlighted variables (Green at the left) are considered in the model. The other variables are found to be highly correlated with the considered ones and opted out in the final selection of variables.

To date, energy system transitions have exhibited many different modes and phases regarding their nature, forms of usage, and dynamics in the shift from one stage to the next (Geels et al., 2017; Crespo del Granado et al., 2018; Sung and Park, 2018; Köhler et al., 2019). Nonetheless, concerning the current context of sustainability affected by climate change from greenhouse gas emissions, Granado et al. define an energy system transition as the pathways through which the transformation of fossil-fuel-based power generation systems to emissionless and eco-friendly systems may take place (Granado, et al., 2018). A clear and deeper understanding of the energy system transition may deliver essential insights and directions for stakeholders to formulate and implement plans, policies, and strategies for the energy and power sector to prioritise sustainability (Gulagi et al., 2020). However, climate change is not the only driver behind the Green Transition (Bumpus and Martin, 2015). It is rather firmly propelled and regressed by many other socioeconomic and technical factors essential to (Dong and Mori, 2017; Robertson Munro and Cairney, 2020). Therefore, to comprehend and explore today's energy system transition to realise significant impacts on addressing the environmental suitability concerns, socioeconomic and technical issues must be considered with substantial priority (Burke, 2020)

2.11.1.7 Goodness-of-Fit Statistics

After using graphical methods to estimate the goodness of fit, the goodness-of-fit statistics should be examined. In Matlab, the Curve Fitting Toolbox™ software provisions the following goodness-of-fit statistics (Matlab, 2023) for parametric models which were used in fitting the datasets to the trendlines in this research:

- The sum of squares due to error (SSE)
- R-square
- Degrees of freedom for error (DFE)
- Adjusted R-square
- Root mean squared error (RMSE)

2.11.1.8 Sum of Squares Due to Error (SSE)

This statistical metric quantifies the overall discrepancy between the observed response values and the fitted response values. The term "sum of squared residuals" is commonly referred to as SSE in academic literature. A value approaching zero signifies that the model possesses a diminished random error component, hence enhancing its predictive utility (Matlab, 2023). The modelling carried out in this study tried to reach its smallest value while simulating every scenario.

2.11.1.9 R-Square

This statistical measure quantifies the degree of success in elucidating the variability observed in the dataset. In alternative terms, the coefficient of determination (R-square) can be defined as the squared value of the correlation between the observed response values and the projected response values (Matlab, 2023). It is alternatively referred to as the square of the multiple correlation coefficient and the coefficient of multiple determination. The coefficient of determination also referred to as R-square, is a statistical measure that ranges between 0 and 1. A higher value of R-square suggests that a larger proportion of the variability in the data is explained by the model. For instance, a coefficient of determination (R-square) of 0.8234 indicates that the regression model accounts for 82.34% of the overall variability observed in the data relative to the mean (Matlab, 2023).

Increasing the number of fitted coefficients in a model can lead to an increase in R-square, but this improvement may not necessarily translate into a practical enhancement in the model's fit. To mitigate this scenario, it is advisable to utilise the degrees of freedom adjusted R-square statistic as elucidated subsequently. It should be noted that in equations without a constant term, it is possible to obtain a negative R-square value. If the fit is less accurate than just fitting a horizontal line, the R-square value will be negative, as R-square represents the proportion of variance accounted for by the model. In this particular scenario, it is not appropriate to interpret R-square as the square of a correlation coefficient. These circumstances suggest that the inclusion of a constant component in the model is necessary (Matlab, 2023). Fortunately, most of the independent variables' trendlines obtained significantly healthy R-square values (~0.9) except one or two (Table 9).

2.11.1.10 Degrees of Freedom Adjusted R-Square

The aforementioned statistic utilises the R-square statistic and incorporates adjustments based on the residual degrees of freedom (Matlab, 2023). The residual degrees of freedom can be mathematically described as the difference between the number of response values, denoted as n, and the number of fitted coefficients, denoted as m, which are estimated from these response values (Matlab, 2023).

$$v = n - m, \text{ (Equation 10)}$$

Here, the variable v represents the difference between the number of independent pieces of information, denoted by n, and the number of dependent pieces of information, denoted by m (Matlab, 2023). This equation is used to determine the number of independent pieces of information needed to calculate the sum of squares. It should be noted that in cases when parameters have constraints and one or more of the estimates reach these bounds, Matlab optimally fixes such estimates. The number of parameters contributes to an increase in the degrees of freedom (Matlab, 2023).

2.11.1.11 Confidence and Prediction Bounds

The Curve Fitting Toolbox™ software package of MATLAB provides the capability to compute confidence bounds for the coefficients obtained from fitting a curve, as well as prediction bounds for either new observations or the fitted function (Matlab, 2023). Moreover, in the context of prediction boundaries, it is possible to compute simultaneous bounds that consider all predictor values collectively, or non-simultaneous bounds that consider individual predictor values separately. The numerical representation of the coefficient confidence bounds is provided, whereas the prediction boundaries are visually depicted and can also be accessed in numerical form (Matlab, 2023).

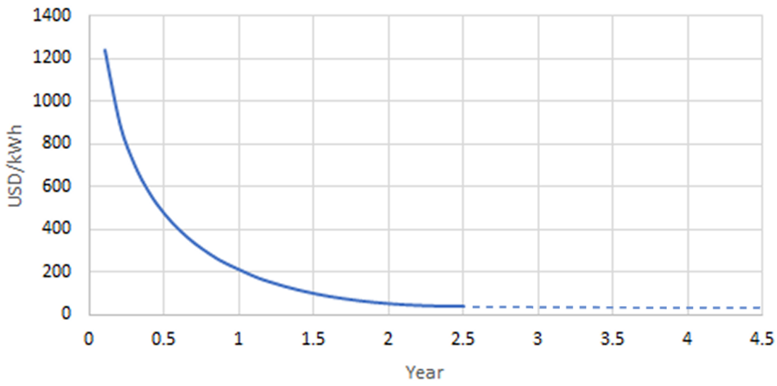
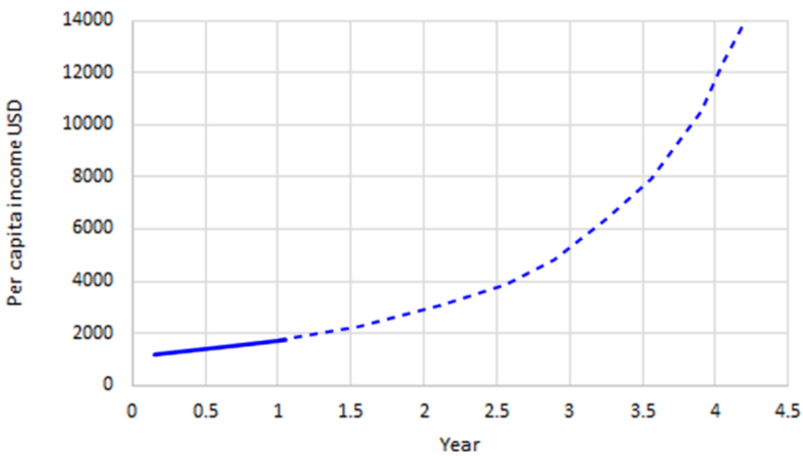
Confidence and prediction boundaries establish the lower and upper limits of the corresponding interval, hence determining the breadth of the interval (Matlab, 2023). The magnitude of the interval signifies the level of uncertainty about the estimated coefficients, the projected observation, or the projected fit. For instance, a significantly large interval for the estimated coefficients may suggest the need for a larger dataset during the fitting process to make more conclusive statements regarding the coefficients (Matlab, 2023).

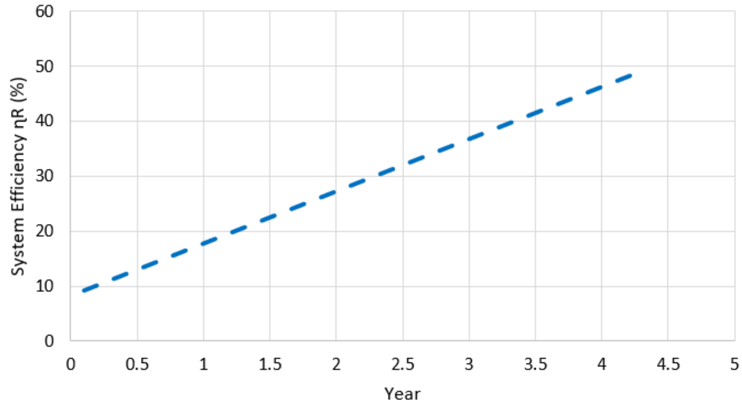
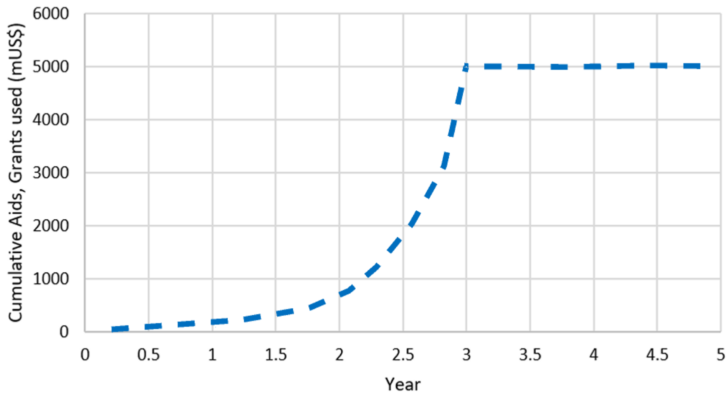
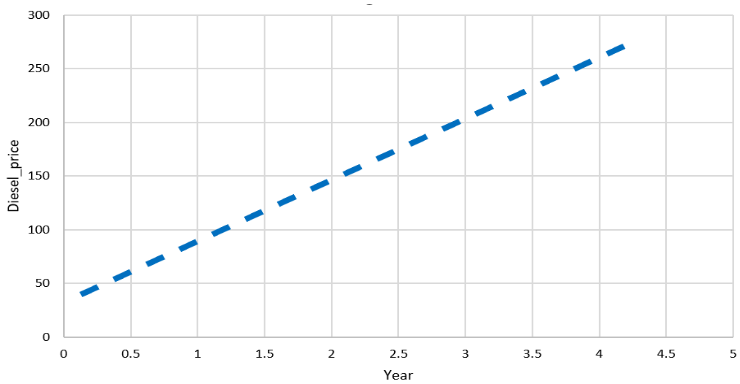
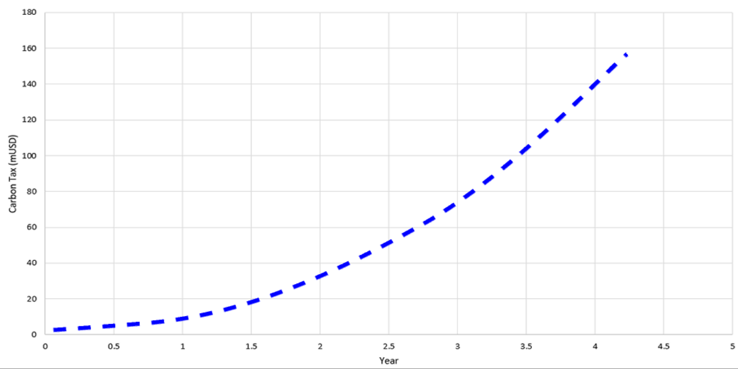
The boundaries are established with a specified level of certainty. The level of certainty is commonly set at 95%; however, it has the potential to vary throughout a range of values, including but not limited to 90%, 99%, 99.9%, and so forth. As an illustration, one may consider the desire to maintain a 5% probability of error in the prediction of a novel observation. Consequently, one would compute a prediction interval with a confidence level of 95%. This interval signifies a 95% confidence level that the new observation lies within the lower and higher prediction bounds (Matlab, 2023). In the case of the variables selected for the modelling, the fitted curves had a 95% confidence level. The magnitude of 95% is a widely accepted level across the world (Gavin, 2022).

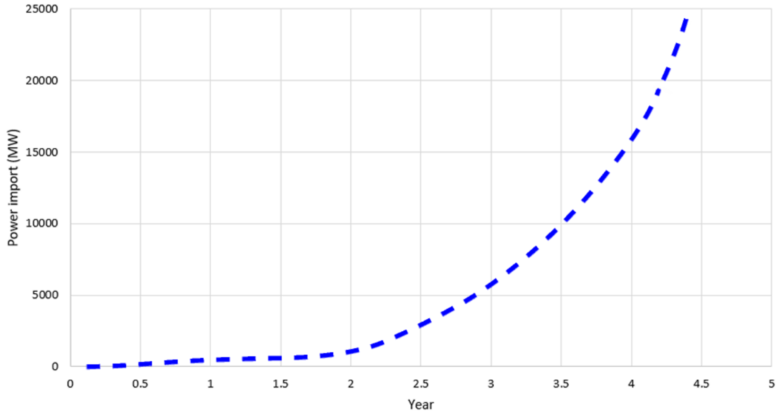
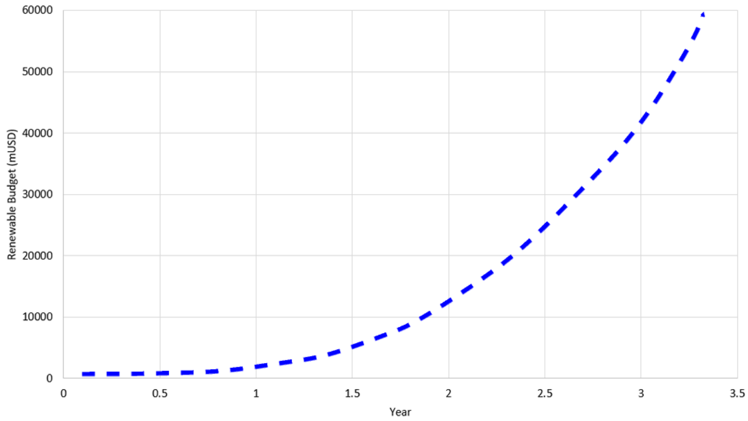
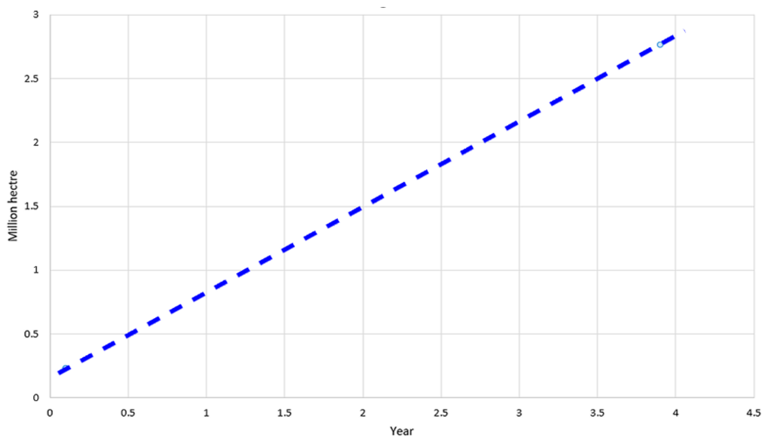
2.11.1.12 Trend functions of the variables

The year-wise magnitudes of each of the considered variables were collected from the government of Bangladesh (See 2.11.3). Then the trendlines for each of them concerning time were graphically determined in MATLAB using a curve fitting tool. Each of the 9 variables has been projected to 2050 as shown in Table below. Capping of values was applied as either an upper or lower bound. For example, WB and Bangladesh Government projected not less than 12000 USD/ per capita to be the income by 2050 (Figure 27). According to the Ministry of Foreign Affairs, total renewable grants would not surpass 5 billion USD by 2030 and then it will be ceased as Bangladesh will graduate from developing state status (MoFA, 2020). All other projection boundary values are considered to be within reasonable limits to 2050.

Table 9 Trendlines for each of the independent variables fitted in MATLAB with their statistical features.

Variable	Trendline Function	Fitness Features	Plot
ESS price= f(x) **x= time, half yearly, scaled down to 0.1= 6 months (from 2010-2050)**	General model: f(x)= a*log(x)+c*x, if f′(x)≥0, f(x)=10, Coefficients (with 95% confidence bounds): a = -529.4 (-559, -499.8); c = 210.3 (190.2, 230.4)	Goodness of fit: SSE: 4.474e+04, R-square: 0.9773, Adjusted R-square: 0.9761, RMSE: 49.86	
Income (USD/Per capita) = f(x); x= time, yearly, scaled down to 0.1= 12 months (from 2000-2050)	General model: f(x) = 50000/ (1-a*(exp(x^b))) + c; if x=4.1, f(x)=12000; Coefficients (with 95% confidence bounds): a = -3.735 (-4.492, -2.977); b = -1.164 (-1.528, -0.8001); c = 962.2 (792.6, 1132)	Goodness of fit: SSE: 1.142e+05; R-square: 0.9614; Adjusted R-square: 0.9528; RMSE: 112.6	

System Efficiency (%) = f(x), x= time, yearly, scaled down to 0.1= 12 months (from 2010-2050)	Linear model: f(x) = a*(sin(x-pi)) + b*((x-10)^2) + c; if f(x)≥50, f(x)=50; Coefficients (with 95% confidence bounds): a = -0.719 (-5.85, 4.412); b = -0.4811 (-0.6845, -0.2777; c = 56.2 (35.53, 76.87)	Goodness of fit: SSE: 0.6881, R-square: 0.9956, Adjusted R-square: 0.9946, RMSE: 0.2765	
Cumulative Grants, Aids (mUSD)=f(x); x= time, yearly, scaled down to 0.1= 12 months (from 2010-2050)	General model: f(x) = 5000/ (1-a*(exp(x^b))) + c*x; if f(x)≥5000, f(x)=5000; Coefficients (with 95% confidence bounds): a = -10.75 (-652.9, 631.4);b = -1.163 (-29.65, 27.32);c = 121.4 (29.64, 213.2)	Goodness of fit: SSE: 1348; R-square: 0.9513;Adjusted R-square: 0.9405;RMSE: 12.24	
Diesel Price (USD/barrel) ; x= time, yearly, scaled down to 0.1= 12 months (from 2010-2050)	General model:f(x) = a*x + c; Coefficients (with 95% confidence bounds):a = 55.341 (-39.886, 65.041); c = 34.395 (18.15, 121.4)	Goodness of fit: SSE: 127.8; R-square: 0.9765; Adjusted R-square: 0.9713; RMSE: 3.769	
Carbon Tax (mUSD); x= time, yearly, scaled down to 0.1= 12 months (from 2010-2050)	General model:f(x) = a*x2 – b*x +c; Coefficients (with 95% confidence bounds): a = 10.046 (--46.82, 126.7); b = 7.9468 (-7.824, 18.96); c=7.6784	Goodness of fit: SSE: 56.69; R-square: 0.8414; Adjusted R-square: 0.40294; RMSE: 1.292	

Green power import (MWp); x= time, yearly, scaled down to 0.1= 12 months (from 2010-2050)	General model: f(x) = a*x^3 – b*x^2 + c*x -d, where x is normalised by mean 0.675 and std 0.3957; Coefficients (with 95% confidence bounds): a = 466.6 (100, 600); b = 1063.4 (900, 1200); c= 810.26; d= 186.87	Goodness of fit: SSE: 751.9; R-square: 0.9197; Adjusted R-square: 0.9516; RMSE: 8.671	
Renewable budget (mUSD) (Allotted from public fund) ; x= time, yearly, scaled down to 0.1= 12 months (from 2010-2050)	General model: f(x) = a*exp(b*x), where x is normalised by mean 0.675 and std 0.3957, Coefficients (with 95% confidence bounds): a = 0.6204 (5.432, 8.867), b = 3.421 (2.131, 4.476)	Goodness of fit:SSE: 47.89, R-square: 0.9823, Adjusted R-square: 0.9205, RMSE: 2.188	
Land availability (Million Hectare) ; x= time, yearly, scaled down to 0.1= 12 months (from 2010-2050)	Linear model: f(x) = p1*x + p2 where x is normalised by mean 0.675 and std 0.3957; Coefficients (with 95% confidence bounds): p1 = 0.6667 (-0.1743, 0.9468); p2 = 0.1667 (-0.1966, 0.6955)	Goodness of fit: SSE: 1.504; R-square: 0.7606; Adjusted R-square: 0.95; RMSE: 0.3878	

The trendline functions played a significant role in the modelling of the sociotechnical capacity for renewable transition while being used as independent variables.

2.11.1.13 Iteration approach to solve the set of non-linear equations

The GAM modelling uses VAR approach and Levenberg-Marquardt algorithm in Matlab to attain the solutions. Similar to other methods used for numeric minimisation, the Levenberg-Marquardt algorithm follows an iterative process (Ranganathan, 2004). To initiate a minimisation process, an initial guess for the parameter vectors was provided to determine the plausible combination set of coefficients for which the modelled curve fits closer to the given values. In situations when there is a single minimum, an unguided conventional estimate will suffice. However, in scenarios where many minima exist, the algorithm will only converge to the global minimum if the initial estimate is already in proximity to the ultimate solution (Gilmore, 2017).

The convergence criteria for the Marquardt-Levenberg algorithm are achieved when the change in the sum of squares of the residuals is below a certain tolerance level or when the maximum number of iterations is reached (Lourakis and Argyros, 2005). In each iteration step, the parameter vector β is placed by β+ δ.

The set of the model equations may look like the following:

In year 1 (t=1),

$$R_1 = \frac{A}{1 - B * e^{(\{k_1 f_1(t1) + k_2 f_2(t1) + k_3 f_3(t1) + k_4 f_4(t1) + k_5 f_5(t1) + k_6 f_6(t1) + k_7 f_7(t1) + k_8 f_8(t1) + k_9 f_9(t1)\})}}$$

$$\Rightarrow R_1 - \frac{A}{1 - B * e^{(\{k_1 f_1(t1) + k_2 f_2(t1) + k_3 f_3(t1) + k_4 f_4(t1) + k_5 f_5(t1) + k_6 f_6(t1) + k_7 f_7(t1) + k_8 f_8(t1) + k_9 f_9(t1)\})}} = 0 \quad \text{(Eq - 11)}$$

In year 2 (t=2),

$$R_1 = \frac{A}{1 - B * e^{(\{k_1 f_1(t2) + k_2 f_2(t2) + k_3 f_3(t2) + k_4 f_4(t2) + k_5 f_5(t2) + k_6 f_6(t2) + k_7 f_7(t2) + k_8 f_8(t2) + k_9 f_9(t2)\})}}$$

$$\Rightarrow R_1 - \frac{A}{1 - B * e^{(\{k_1 f_1(t2) + k_2 f_2(t2) + k_3 f_3(t2) + k_4 f_4(t2) + k_5 f_5(t2) + k_6 f_6(t2) + k_7 f_7(t2) + k_8 f_8(t2) + k_9 f_9(t2)\})}} = 0 \quad \text{(Eq- 12)}$$

Similarly,

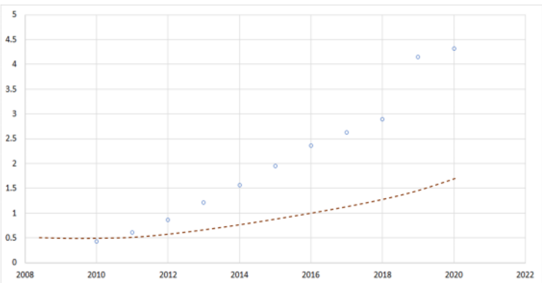
In year n (t=n),

$$R_1 = \frac{A}{1 - B * e^{(\{k_1 f_1(tn) + k_2 f_2(tn) + k_3 f_3(tn) + k_4 f_4(tn) + k_5 f_5(tn) + k_6 f_6(tn) + k_7 f_7(tn) + k_8 f_8(tn) + k_9 f_9(tn)\})}}$$

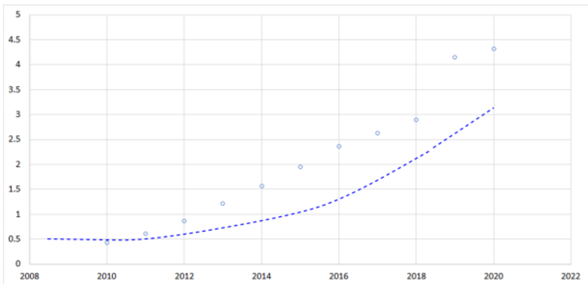
$$\Rightarrow R_1 - \frac{A}{1 - B * e^{(\{k_1 f_1(tn) + k_2 f_2(tn) + k_3 f_3(tn) + k_4 f_4(tn) + k_5 f_5(tn) + k_6 f_6(tn) + k_7 f_7(tn) + k_8 f_8(tn) + k_9 f_9(tn)\})}} = 0 \quad \text{(Eq- 13)}$$

Setting up upper and lower limits for each k (Trust region), a set of k is obtained in MATLAB solving the above equations simultaneously using *fsolve* (MATLAB solver tool that uses Vector autoregression solution technique based on Levenberg-Marquardt algorithm here). Varying the limits, different sets of k are obtained, and checks are performed whether the modelled fit gets closer to the given curve points. Table 10 gives the idea of how the variation in search range converges the data points to the closer fitting.

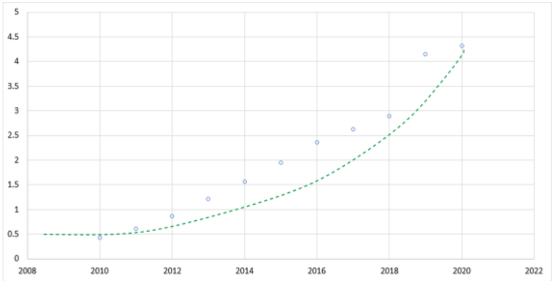
Table 10 Converging towards the given points through the variance in the initial search range of the parameters (X axis-Year vs Y axis-Renewable power generation in TWh).



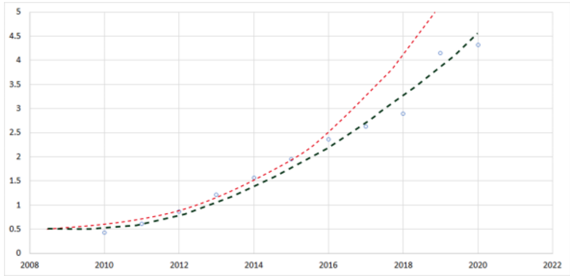
For a set of initialised values (k_{lim}) for the parameter range, the curve goes far from the actual data points. (R^2=0.44)



Better intuition in the initial parameter limit (klim) guess gets it closer (R^2= 0.67)



R^2=0.76



R^2=0.87 (Red), 0.91 (Green)

When considering these codes, it is crucial to adhere to three significant factors for achieving iterative convergence. Initially, it is essential to note that the discretised equations, including those on per capita income, levelised cost of electricity (LCoE), carbon tax, and others, are considered to have achieved convergence after they satisfy a predetermined tolerance level at each nodal point (Lu, Dong and Liu, 2020). Furthermore, it can be observed that the numerical answer remains constant even when extra iterations are performed. Then, the overall scalar balances between variables are determined. Each of the iterations were carried out to reach a practically plausible trend. Throughout the numerical procedure, the imbalances (errors) of the discretised equations are observed. These imbalances are commonly known as the residuals of the system of non-linear algebraic equations. They quantify the degree of imbalances that arise from these equations and halt the numerical process once a predetermined tolerance level is achieved. To achieve adequate convergence, the residuals must decrease in magnitude as the numerical process advances. If the imbalances continue to increase, as shown by the rising residual values, the numerical solution might be categorised as unstable (divergent) (Hairer, 2014). However, following a long chain of iterations for different parameter limits, a plausible fit was achieved in this study. Extrapolating the curve for forecasting to 2100 gives the following imagery:

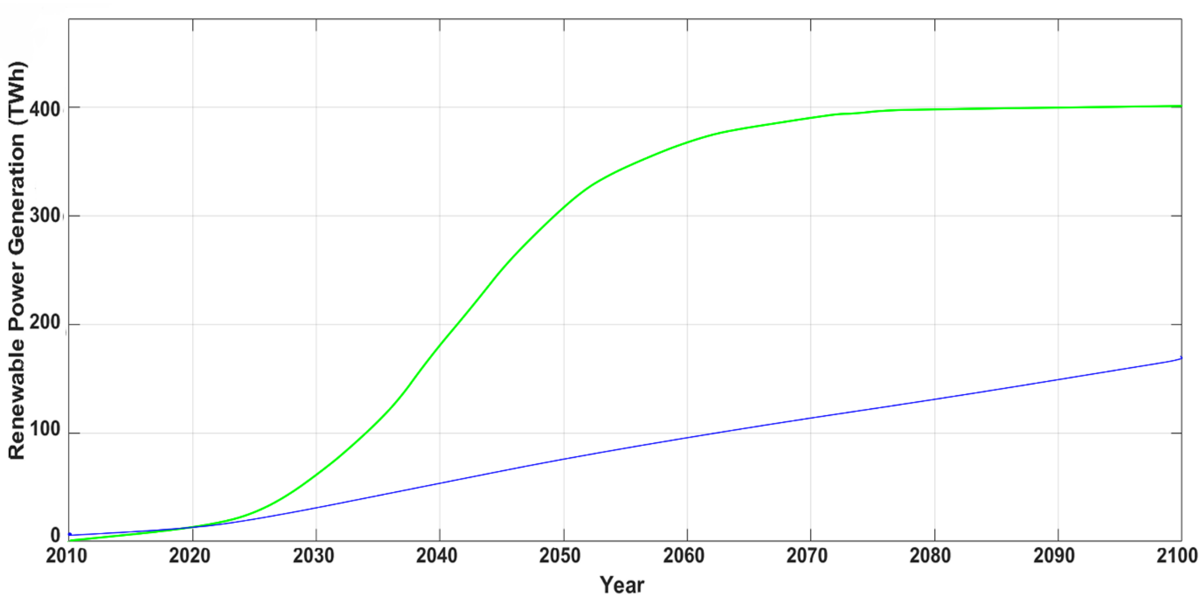


Figure 16 Renewable generation capacity Prediction for Bangladesh from 2020-2100 (Following Variables' Projections —— and Business as Usual (Linear extrapolation) ——)

2.11.1.14 The rationale behind choosing the Logistic-nonlinear VAR technique to solve the GAM model

Some of the key reasons to select Logistic-nonlinear VAR technique (used by Matlab) to obtain the GAM model over others are outlined below:

With the consistent development of Bangladesh's Economy and renewable technology over the last decade, almost all the variables show nearly smooth changes over time that create pseudocollinearity where Vector Autoregressive modelling is expected to be helpful.

1. The variables' year-wise trends are mostly non-linear considering available data trends and common worldwide tendencies (Lauret et al., 2012).
2. The simulation is intended to be multivariate or univariate.
3. A high linear correlation among the variables was found which is unrelated in reality (Mathews et al., 2019).
4. The time series dataset (significant for renewable expansion) is limited to only a ten-year data period.
5. There may be many different sets of coefficients satisfying the modelling equation.
6. The independent variables are nonlinear concerning time or the dependent variable.
7. Diverse kinds of non-linearity are found in the trendlines of the independent variables (Table 11).

Vector autoregression (VAR) statistically captured the relationship between multiple quantities as they change over time. VAR is a type of stochastic process model. The VAR models generalise the single-variable (univariate) autoregressive model allowing for multivariate time series (Bolwig et al., 2019; Harper et al., 2019). The incumbent model assumed nine independent time-series variables to cause the maximum exploitable renewable power generation capacity. Later, stochasticity will be induced using Monte Carlo simulation and applying periodic shocks from the natural calamities (Floods, cyclones etc.) to obtain more realistic outcomes. Since, in the incumbent study, the renewable power generation capacity is considered a function of nine socioeconomic and sociotechnical capacities that are temporally changeable, and a multivariate state is very likely to occur among them, the VAR appears appropriate to use (Bai, 2000).

Many modelling techniques have been used to model the energy transition across global and regional landscapes, including a few in Bangladesh. VAR models are often used in economics and the natural sciences, where spatiotemporal dynamics are prevalent. Several studies on energy transition modelling also used VAR as the core modelling tool (Bai, 2000; Sung & Park, 2018). Multiple structural changes are often well-fitted in VAR models, which is proportional to the Bangladesh perspective, where multiple socioeconomic variables have been considered for the modelling. However, this hybrid technique has not been used among the available models developed in Bangladesh. The proposed model may be a novel addition to the existing knowledge pool, considering the inclusion and compilation of the contents in the context of a developing country like Bangladesh, where many endemic intrinsic and extrinsic factors strongly influence the renewable transition.

2.11.2 Limitations of using VAR technique to solve the GAM model function and minimisation

In the autoregressive model, each independent variable has a temporal equation denoting its evolution over time that has been embedded in the proposed model. The generic VAR equation includes the variable's lagged (past) values, the lagged values of the other variables in the model, and an error term (Abdallah *et al.*, 2020). The simulation is intended to be multivariate or univariate, where one or more independent variables will be changed to see the effect on the dependent variable. VAR models can handle this issue more comfortably than others like ARIMA or VARIMA, as VAR does not essentially require a uniform periodicity in their time-series data (Bai, 2000; Chassin, Fuller and Djilali, 2014). Bangladesh's data sets may exhibit such non-uniformity that this technique can address.

2.11.2.1 Addressing Multicollinearity

Despite the linear dependence among variables that predict a transitioning domain caused by pseudocollinearity, it should be carefully handled in its modelling, considering spatiotemporal dynamics. The effects of predictor collinearity in traditional linear regression models is a widely considered issue (e.g., ordinary least square estimation in linear regression models). For instance, it becomes challenging to distinguish between the unique effects of each variable when multiple variables show a high degree of correlation. Additionally, in model transfer scenarios, models with linearly correlated variables are more likely to make mistakes in extrapolated cases (Dormann et al., 2013; Meloun, Militk, Hill, & Brereton, 2002). Ideally, collinearity should not be considered for all but practically significant variables (Dormann et al., 2013; Tanner, Papeş, Elmore, Fuhlendorf, & Davis, 2017). However, because many commonly used environmental predictors are highly linked and, or non-independent, the issue of collinearity is challenging to avoid when choosing practically meaningful variables (Jiménez-Valverde, Nakazawa, Lira-Noriega, & Peterson, 2009). By choosing variables whose correlation coefficients are below a certain threshold (e.g., |r| 0.7 in Dormann et al. (2013) or 0.4 in Suzuki, Olson, & Reilly (2008)), one can reduce the possibility of collinearity's adverse effects in practice. However, there are two opposing viewpoints on collinearity in transition. It is wiser to consider that the guidelines established for classical regression models may not immediately apply to all transition modelling. According to some, the transition's ability to control model complexity by undervaluing redundant variables makes the algorithm resistant to collinearity problems (Elith et al., 2011; Phillips & Dudk, 2008; Shcheglovitova & Anderson, 2013). Others claim that most spatiotemporal transition models can only partially handle collinearity. Therefore, the user should try to decrease predictor collinearity (Merow, Smith, & Silander, 2013). Even though both perspectives are well-represented in the literature on ENM, to the authors' knowledge, no empirical studies have been done to determine how predictor collinearity affects transition models. However, the proposed model will try to justify the model's applicability through simulated outcomes by independently varying variables.

Predictor collinearity can affect regression-type models in two different ways, depending on the correlation structure of the predictor variables in the training and testing (or projecting) regions: (a) model transfer; and (b) model training (i.e., collinearity shift). The issue of collinearity in transition must therefore be considered from the perspective of model transfer, which comprises transporting a model across space and/or time to consider diverse environmental conditions (Elith & Leathwick, 2009; Guisan & Thuiller, 2005; Peterson et al., 2011). When models are moved, collinearity shift may end up being the main mechanism; when models are not moved, the mechanism that influences the modelling will likely determine the collinearity effects. Another factor influencing model performance in the model transfer is model extrapolation, or the ability to generate predictions in environmental settings other than those used in model training (Gelman & Hill, 2007). According to past studies, environmental novelty is negatively connected with model performance (Fitzpatrick et al., 2018; Owens et al., 2013; Qiao et al., 2019). Therefore, a transition model scenario should include environmental novelty and collinearity shift.

Table 11 Linear Correlation among the Influential variables for Green Power Transition in Bangladesh

Variables	The income per capita US$	System Efficiency ηR (%)	PV price (monocrystalline), LCoE of Solar (USD/MWh)	Cumulative Aids, Grants (mUS$)	Carbon Tax mUS$	Green Power Import	Renewable Budget (mUS$)	ESS price USD/KWh	Land availability (mH)	Renewable Energy (TWh)
The income per capita US$	1.000									
System Efficiency ηR (%)	0.994	1.000								
PV price (monocrystalline), LCoE of Solar Power (USD/MWh)	-0.919	-0.925	1.000							
Cumulative Aids, Grants (mUS$)	0.795	0.840	-0.710	1.000						
Carbon Tax (mUS$)	0.978	0.968	-0.926	0.726	1.000					
Green Power Import (MW)	0.901	0.925	-0.802	0.933	0.813	1.000				
Renewable Budget (mUS$)	0.961	0.976	-0.863	0.919	0.903	0.979	1.000			
ESS price USD/KWh	-0.944	-0.933	0.964	-0.643	-0.970	-0.750	-0.847	1.000		
Land availability (mH)	0.838	0.876	-0.748	0.988	0.761	0.969	0.951	-0.682	1.000	
Renewable power Generation (TWh)	0.995	0.986	-0.930	0.754	0.990	0.861	0.936	-0.966	0.795	1.000

The table above demonstrates the collinearity among the variables based on the collected data. It is derived using the linear regression technique varying the variables against each. Most of the variables showed significant collinearity to others individually. It gives the impression that variables are linearly related to each other to a significant extent. However, the reality and logical reasoning about the progressive trend of the variables suggest something else since they may not act linearly in the future.

Considering the development of Bangladesh's economy and renewable technology over the past decade, almost all the development indices show nearly consistent changes over time. The time-series data of those variables are very likely to express pseudo-collinearity (Assaf, Tsionas and Tasiopoulos, 2019) in numerical correlation tests. However, the changes would not remain consistent shortly according to the socioeconomic development dynamics of the other regions. Vector Autoregressive technique to solve time-series set is expected to reduce errors when the changes exhibit predictable nonlinear patterns effectively. For example, linear economic growth rises exponentially after a certain ceiling and then goes flat again (Kwasnicki, 2013b). In that case, nonlinear VAR may be an effective tool to model outcomes when many variables may indicate simultaneous but mutually excludable changes. Using different solution ranges to determine the regression coefficients for the solution of the renewable power generation function, the most plausible set of coefficients was obtained. The simulation script coded in MATLAB has divided the regression function into several sub-functions to solve this issue. To facilitate an individual contributary aggregation, each function represents independent variables separately. This technique minimises the multicollinearity problem to a significant level. For example, instead of a regression model as $y_t = k_1x_1+k_2x_2+k_3x_3+k_4$, it is more rational to use $y_t = k_1(\log x_1) + k_2x_2^{2.43} + k3e^{x3} + k_4$, when the variables x_1, x_2 and x_3 are showing non-linear patterns respectively mentioned in the second expression. This study used this as a novel approach in the transition modelling context of Bangladesh.

Structural change in VAR is an essential problem for at least two reasons (Bai, 2000). The first relates to VAR's popularity as a modelling tool in macroeconomics. The second has to do with the findings of Bai, Lumsdaine, and Stock (1998). These authors argued that the precision of the break-point estimators could not be improved upon by acquiring more comprehensive data but could be significantly improved upon by adding series with common breaks. Analysing multiple equations with common breakpoints can yield more precise estimates of the change points. This recommendation is incorporated in the proposed model and has not been used in the previously developed models for a Bangladeshi context. A comparable parallel scenario is remarkably present in the data available in the Bangladeshi perspective regarding various sociotechnical variables for use in the model. As a result, the structural change problem in VAR is of theoretical and practical importance. The results derived in this paper are, of course, also applicable to a univariate time series. They are also applicable to cross-section regression models and exceedingly unrelated regressions (Bai, 2000) found in the selected variables for this study.

2.11.2.2 Use of Levenberg-Marquardt and Trust Region algorithms

In mathematics and computers, non-linear least squares issues are often resolved using the Levenberg-Marquardt algorithm (LMA or just LM), also referred to as the damped least-squares (DLS) approach (Yuan, 2015). These minimisation issues are particularly prevalent when fitting least squares curves. The LMA interpolates the Gauss-Newton algorithm (GNA) and the gradient descent method. Because the LMA is more resilient than the GNA, it frequently finds a solution even when it starts far from the final minimum. The LMA often runs slower than the GNA for well-behaved functions and suitable starting values. The trust region technique to Gauss-Newton can also be applied to LMA. In contrast, a trust region in mathematical optimisation is a subset of the objective function's region approximated by a model function (often a quadratic or polynomial). The region is either expanded or reduced depending on whether a good approximation of objective function can be obtained inside the trust region (Yuan, 2015).

A nonlinear challenge occurs when an objective or constraint cannot be described as a linear function without compromising some fundamental nonlinear element of real-world situations. The modelling challenges here include such impulses. The nonlinear programming techniques guess the variable vector x (known as iterates and indicated by the super or subscripts x_1, x^2, x3, etc.) to determine the best value (Erik Gregersen, 2019). The optimal x value is frequently not feasible. In these cases, one must select a local optimum, the best value in a potential solution zone. Each iteration is determined by knowledge of the early constraint and the objective function. Most nonlinear programming algorithms address one class of problems (Yuan, 2015). While some algorithms target convex quadratic programming issues, others target huge, smooth unconstrained problems where the matrix of second derivatives of f(x) has few nonzero values and is difficult to evaluate. Levenberg-Marquardt and Trust Region algorithms conduct the regression among the variables to obtain the "k" values required to deduce and construct the final model function. It is a familiar technique widely used in built-in regression software like SPSS or STATA. This model is coded in MATLAB, as different variables had different trends.

Conceptually, in the Levenberg–Marquardt algorithm, the objective function is iteratively approximated by a nonlinear surface, and then using a linear solver, the estimate is updated[17]. If the initial estimate is too far from the optimum, it alone may not converge properly. For this reason, the algorithm instead restricts each step, preventing it from stepping beyond the acceptance limit (Kanzow, Yamashita and Fukushima, 2004). On the other hand, the trust region is a subset of the region of the objective function that is approximated

[17] https://web.archive.org/web/20200414204913/https://www.gnu.org/software/gsl/doc/html/nls.html

using a model function (often a quadratic) (Yuan, 1990). If an adequate model of the objective function is found within the trust region, then the region is expanded; conversely, if the approximation is poor, the region is contracted. The data matrix of the variables in the proposed model produces an abstract 10-dimensional space (for nine independent and one dependent variable) where each yearly set of values generates a curvilinear depiction of the regression function. Thus, a ten-year dataset produces ten different curves. The Levenberg–Marquardt solver tries to detect intersection points among those curves as the solutions of the variable coefficients (Matlab, 2023). The optimisation is done by varying the trust region fixation while coding or simulating the operation. In this thesis, the model was run by carrying out several iterations, varying the trust regions to find a plausible set of values for the variable coefficient conforming to the real occurrences.

2.11.2.3 Addressing the identification problem between the demand and supply sides

This measure is essentially designating a transition capacity model where the amount of renewable electricity generation is assumed to be a logistic function of those sociotechnical and socioeconomic factors. The model intends to introduce a novel approach to simulate Bangladesh's future renewable generation capacity based on the recent changes in pertinent sectors and individual predictions (rationally deduced) on each independent socioeconomic/sociotechnical variable. This approach was taken as Bangladesh intends to increase its renewable power generation according to its socioeconomic/technical capacities. Then, in turn, this renewable power function was substituted to a temporal function that gives the future capacity of Bangladesh for renewable power in the upcoming years. Therefore, the categorisation of demand and supply side variables is insignificant as both influence the transition and can be incorporated within the model with proper quantification/indicators.

Incorporating a logistic function into an autoregressive model is a relatively rarely used combination of techniques (usually used separately). However, through deeper and wider investigation and exploration, it can be assessed for its endorsement as an acceptable approach for further use. However, since the autoregression using a ten-year time series with a logistic model function produced a plausible fit (see the table below), it may be considered an applicable approach in a Bangladesh context where the selected variables showed acceptable consistency during the simulation.

2.11.3 Base Data for Sociotechnical Capacity Modelling for Renewable Transition in Bangladesh

Table 12 Variable data for modelling (sources are mentioned in annex 1, The monetary exchange rate of USD is as per the July 2022 rate)

Year	The income per capita US$	System Efficiency ηR (%)	PV power price (monocrystalline), LCoE of Solar (USD/MWh)	Cumulative Aids, Grants used (mUS$)	Diesel price USC/Litre (Normalised at 2022 exchange rate)	Carbon Tax mUS$	Green Power Import (MW)	Renewable Budget (mUS$)	Land Availability (mH)	Renewable Power (TWh)
2010	928	9.5	190	16	44	6	0	0.5	0.2	0.44
2011	955	10	125	23	46	7	0	1	0.3	0.61
2012	1054	11	120	33	51	6	0	2	0.4	0.87
2013	1184	12	110	47	56	7	0	3	0.5	1.22
2014	1316	13	100	60.	61	6	14	4	0.9	1.57
2015	1465	14	97	78	68	7	14	7	0.5	2.05
2016	1610	15	83	90	65	8	14	9	0.4	2.36
2017	1752	16	71	101	80	9	20	11	0.3	2.65
2018	1909	17	60	111	86	6	30	15	0.4	2.9
2019	1994	19	50	121	92	6	40	20	3	3.15
2020	2123	20	40	128	98	5	50	25	0.5	5.33
2021	2591	20	31	186	114	4	100	56	0.7	8.85

The model will generate the maximum possible amount of renewable capacity through the inputs of per capita income (denoting GDP), renewable energy price, system efficiency, foreign aid, Fossil fuel (Diesel) price, ESS price, subsidy, carbon tax, and import and land availability for solar plant installation. The additional possible influential variables are included in a separate table. The simulated transition was shocked by random calamities like a tornado, cyclones, inundations etc., to obtain their impacts on it.

2.11.4 Rationales Behind Conducting Interviews and Surveys

Interviews and surveys are essential tools for gathering information and insights from individuals (Pin, 2019). They allow researchers to collect data, opinions, and perspectives on specific topics or issues. Interviews and surveys provide a way to understand people's thoughts, experiences, and behaviours, which can then be used for various purposes such as market research, academic studies, or decision-making processes (Juster, 1974). They are important methods in policy research as they allow researchers to gather primary data directly from the target population (Stevenson, 2017). These methods provide valuable insights into the opinions, attitudes, and experiences of individuals, which can help inform the development and evaluation of policies. Additionally, interviews and surveys allow for a more systematic and structured approach to data collection, ensuring that a wide range of perspectives are captured (Ponto, 2015).

The major rationale of the proposed open-ended interviews was to gauge and identify the insights, understanding, awareness, plans, visions and knowledge about distinct aspects and prospects of renewable energy in Bangladesh among the influential stakeholders. It is essential since the policy formulation and decision-making regarding power generation, transmission and distribution are predominately dependent upon them in Bangladesh (Alo, 2019). In addition, the plans and socioeconomic, sociotechnical, and geopolitical strategies considered by the government, political entities, and the non-governmental green energy agencies of Bangladesh regarding the penetration of green power mainly contemplated, formulated, and executed by them. Therefore, knowing about their thoughts, acumen and insights regarding the transition is essential to understanding the future of renewable transition in Bangladesh. The model will generate graphical projections based on the numerical data. Nonetheless, state policies are profoundly driven by the sociopolitical and technoeconomic psyche of the associated stakeholders (Lamb et. al., 2019). The questions were asked of the entities from different and interconnected sectors. Most of them are currently incumbents in several crucial positions responsible for planning and executing pertinent activities regarding the power sector. Some of them are likely to engage in similar positions in the future. The study examined their intentions and plans, assessed their practicability, and deduced the viable alternatives (if they want to pursue a fossil fuel power approach), supplementations, and recommendations to realise the pro-green plans. For example: If they claim land scarcity is the main problem, then this study will suggest an approach to maximise the use of rooftop areas of industrial and residential buildings, floating solar technologies etc. Or, if they claim funding is the main problem, the study will suggest augmenting diplomatic steps to bring more foreign investments or green power imports from neighbouring states where the potential is greater and feasible to exploit. This way, the survey and interview questionnaire results were used to fulfil the research objectives. This approach addresses the issue that in a Bangladeshi context, the renewable transition will be driven and operated by the key entities in the government (interviewees), not the mass people of Bangladesh. Several references and rationales in the thesis have supported this view.

2.11.5 Addressing the issues related to socio-economic/sociotechnical capacity and how they are going to be incorporated into a time series forecasting model

Each of the selected model variables profoundly impacts the transition in Bangladesh (among some other countries too). Some are endemic, as Bangladesh has unique demographic, socioeconomic, infrastructural and geolocational features. Those variables were quantified considering the available resources and used in the model as a time series progression for past and predicted future trends. When one issue is dependent upon several issues suggesting a rational spatiotemporal correlation, it can be expressed as a mathematical function. A hypothesis may be formed and checked for plausibility. The hypothesis is: If the variables X1, X2, X3, X4….X9 have caused the generation of Y TWh of renewable power in the year t1 in Bangladesh, then in the year t2, those variables changed to X1’, X2’, X3’, X4’….X9’, will capacitate Y’ TWh of Green Power. If this hypothesis turns true or commensurate with the available time series data, it can be extended for forecasting.

2.11.6 Clarification of resource availability considered in this model

Resource availability was already elaborated in the Renewable Energy Potential in Bangladesh section in the literature review. It was shown that solar is the major exploitable resource, but Bangladesh lacks land for mass-scale solar plants. Land availability is the most crucial factor here. Still, no exact data were found on the lands and their projected escalation in availability in the future due to the shift from agronomy to an industrial economy. However, the study has devised plans and strategies to quantify the land availability projection (never used in any previous study) based on the number of unfarmed lands rising yearly due to industrial shifts and salination due to sea-level rise.

2.11.7 Addressing potential annual, seasonal, and within-day variation in renewable supply

The model incorporates the total yearly renewable electricity generation as the dependent variable. This entity saturates over time with the maximum electricity demand in the future that was modelled assessing the maximum demand of 400 TWh for a combination of saturating economy, appliances, and population. The sociotechnical capacity model tried to predict the future generation capacity to meet the demand from renewable power. It would give policymakers an idea of Bangladesh's maximum socioeconomic and sociotechnical capacity a year in the future to realise green power ventures. The model considered the possible aggregated generation from a system over time, including seasonal variability and energy conversion efficiency. The maximum capacity to generate exploitable renewable power (TWh) is determined from the model, and incorporating the seasonal variability has already been considered when calculating Bangladesh's renewable potential (in aggregated generation).

3 Research Questions and Methodology

The central research question of the research is*:*

How can an electricity transition (from fossil fuel to renewable) modelling in the Bangladeshi context be ideated, conducted, and simulated to capture the dynamics between the transition capacity and several influential socioeconomic/sociotechnical variables?

The auxiliary question may be*: based on the simulated findings how should the policy, plan, and strategies for promoting renewable power in Bangladesh be optimised to tackle the future transition shock, focusing on retaining the projected economic growth to become a developed country by 2041 or beyond?*

To find the answer to these questions, the following ideas have been generated and explored:

1. *Why the sociotechnical capacity for renewable transition is significant in the Bangladesh context?* After discussing the context and background of renewable electricity penetration in Bangladesh, the study pivoted and signified the rationales behind the modelling of sociotechnical capacity for the transition to renewable power in Bangladesh. It determined why it is needed for a better understanding of the transition dynamics propelled by various sociotechnical factors and their interactions.
2. *What model and modelling techniques should be selected to capture the transition dynamics in Bangladesh?* For modelling the renewable power transition capacity of Bangladesh, the study explored a myriad of modelling techniques and previously done models in Bangladesh and other country contexts. It assessed the pertinence and applicability of different models (previously done) in the Bangladeshi context. After carefully examining them, it determined the optimum modelling technique to capture the renewable penetration.
3. *What are the aspects and prospects of available renewable resources in Bangladesh?*
   An extensive study of available literature and data from various sources was conducted to answer this question. Various local and international entities have done qualitative and quantitative research. Recently solar and wind mapping have been done for the entire country, and a vast solar potential has been quantified. Bangladesh has recently mapped renewable potentials based on GIS technology, and the data is available to the author as he serves in the Ministry of Power, Energy and Mineral Resources. The findings will be discussed and analysed for future implications and corresponding modelling for time-bound diffusion.
   The optimum rate of transition will be determined through the consideration of diverse learning curves with pertinent variables, namely the availability of renewables inside and around the country, anticipated GDP growth and affordability, projected escalation in efficiency and price of renewable systems, social/economic cost of emission, energy demand hike etc. Here, multiple regression and other differential equation solution techniques may be used to formulate the model and to deduce the subsequent solution for optimisation. The commensurate degree of raising the renewable share in the energy mix at any instance may be determined from the multiple regression models constructed on these datasets. For example, economic development and energy demand have always exhibited a unidirectional causal correlation in Bangladesh since its independence (Masuduzzaman, 2013). The electricity scenario plays a more significant role in economic growth for a developing country than a developed one (Chen, 2007). Here (Figure 17) is a graphical representation of the correlations:

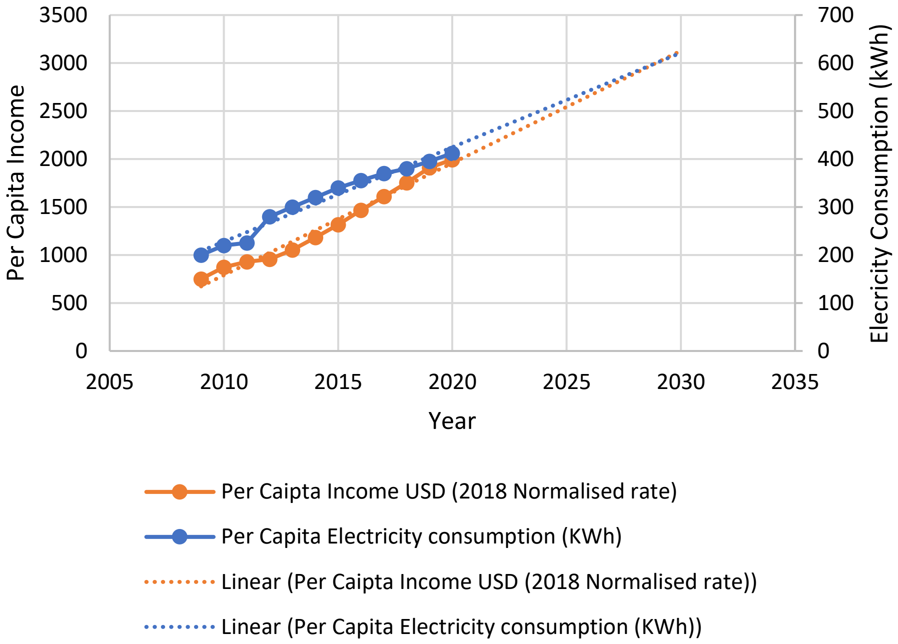


Figure 17: Historical Trends and Future Forecast on Power Demand and GDP of Bangladesh (Dey & Tareque, 2021) (1US$=81.83 Bangladesh Taka in 2011)

Various technoeconomic predictions show (Figure 18) that the price of renewable energy will triumph economically over fossil fuel sources in the next two decades with the technological progress of generation and transmission efficiency (IRENA, 2022). Data on the projected decline in the price of renewables with technological advancement and the increasing power demand (Figure 19) are also available from reliable sources from various academic and government data pools that will remain accessible to the researcher.

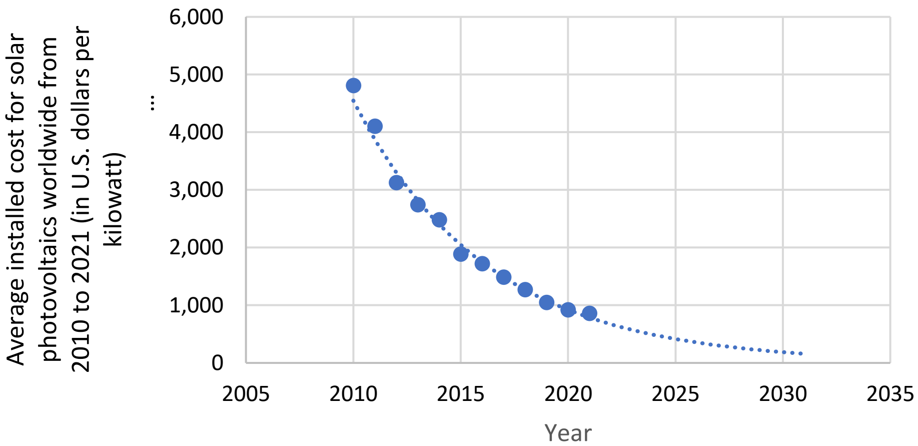


Figure 18: Anticipation of solar power installed cost in future (IRNEA, 2022)

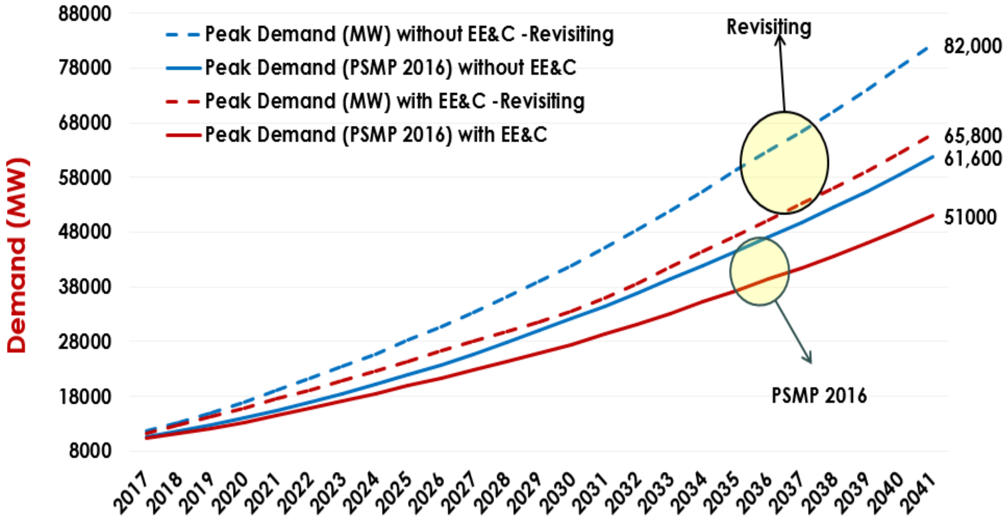


Figure 19: Anticipated Peak Power Demand for Bangladesh (Power System Master Plan with and without EE&C (PSMP, 2016))

These learning curves can be used to generate the regression models for the plans to extrapolate the optimal renewable shares in total power generation. A standard software, MATLAB, was used to regress, extrapolate, and generate models.

4. *What will be the electricity demand in the future in Bangladesh?* To determine the future power demand of Bangladesh, the study carried out a forecast modelling based on the consideration of economic growth, seasonality, EV usage etc. The demand was assumed to be saturated due to stagnation in population growth and industrialisation capacity. Therefore, the demand would rise logistically. That is why the model function would be a Sigmoid one. The saturation amount needs to be inserted into the model as the maximum generation capacity.
5. *What are the challenges and obstacles towards the target of nearly 100% renewables in future?* How can these impediments be overcome? Several challenges and constraints towards greening the existing systems have already been sorted for both developing and developed worlds and are available in peer-reviewed materials and other resources. They will be thoroughly studied and checked for their relevance to the Bangladeshi context. To capture the real scenario, an interview, and a survey among the most influential stakeholders in the transition were conducted. It is indispensable for the Bangladeshi context as all the power generation-related decisions are taken by a few pro-government and government entities so far. The domain is still an oligarchy and there is no sign of any optimistic liberalisation any soon[18]. The decision-making authority will remain among them due to syndication hegemony. Therefore, their understanding and intentions on transition and future power planning is critically significant for the study. The interview and survey responses were used to assess their understanding and intensity of intentions about the renewable transition in Bangladesh. The responses were also used to compare with the simulated outcomes of the model from time to time. The model may display more feasible options for all stakeholders which may not be considered by the policymakers at present. That is why the study decided to conduct the survey and interview.
6. *What should be the roles, responsibilities, and interests of the developed world and the neighbouring states (having surplus renewable resources) in this transition of developing parts? How can Bangladesh exert effective climate/energy diplomacy to achieve the aid?* Being an extremely energy-

[18] https://www.thedailystar.net/opinion/news/power-generation-bangladesh-important-facts-look-2052261

poor country with a sizeable energy-deprived population, Bangladesh is one of the minor carbon emitters on Earth. Unfortunately, it is one of the worst probable victims of climate change with its minimal capacity to handle calamities (Karim *et al.*, 2019). Moreover, being the cheaper option, like many other developing states, electricity from burning fossil fuel (particularly coal) is still the most feasible choice for Bangladesh due to its system capacity for bulk generation to meet the base load dependably. To regress the propagation of this 'no-alternative' action, the developed countries are responsible for fighting climate change as the forerunners on this issue through regional/global partnerships. Cross-border power exchange may be a matter of time everywhere very soon, where renewable resources may be an essential factor. This research sought the array of plausible interests, responsibilities, and roles at both individual and global levels in this nexus. To do so, the proposer delved deeply into the prospects of opening new markets for related commodities by promoting green energy with the help of investment from the developed states. For example, according to Monir Hossain Moni, Japan has aided Bangladesh's infrastructure development (mainly roads and bridges). Consequently, the lion's share of the vehicles running on those Japan-aided roads is manufactured and imported from Japan (Moni, 2006). This research found and converged such scopes in the energy arena.

To determine *the magnitude, aspects, and prospects of available renewable energy resources in Bangladesh,* the researcher delved deeply into the available data, information and other studies undertaken to date. The study extrapolated a power demand curve considering the future population growth, industrial demand, and partial transport decarbonisation.

The focus of this research is to produce and analyse a sustainable transition capacity model for the electrical energy sector of Bangladesh, which is currently primarily covered by fossil fuels. To model the transition capacity, the researcher collected the numerical data for an array of influential variables assumed to be influential over the transition in the last decade. The data was collected from many different agencies and entities of the Government of Bangladesh. The study identified several variables first. Then it selected nine variables as the independent ones influencing the transition. The understanding of the dynamics is in connection to the historical development of the sector and based on the prospect of driving forces such as future policies (Fouquet, 2010). The realistic models are highly diverse in their formulation, underlying conceptual foundation and ontological basis. However, not every model would suit understanding the transition dynamics as long-term, co-evolutionary, multi-dimensional and path-dependent processes. Considering the non-linearity, the complexity of interactions, and the presence of uncertainties and contingencies, the proposed simulation model aims to deliver a better understanding of what form a model should be, as it is called in the recent literature (Holtz G, 2015), a 'transition model'. This model incorporates the profound, pervasive, and polycentric (multi-actor, multi-scale, etc.) transformation of a sociotechnical system, such as an electricity sector, in an intergenerational timescale (Köhler J, 2010).

Being a developing state with poor affordability and limited renewable potential, green transition in the power sector of Bangladesh will predominantly depend upon the financial capacity and technical advancement of the renewable technology itself. Carbon taxation on exported products may influence the transition. Since global warming is a global issue, the environmental impact of Bangladesh's carbon-emitting power systems will not be a concerning issue compared to the total global emissions. Nonetheless, multinational pressures from various groups may influence the movement towards greening the power sector if that creates economic impulses. However, in the case of Bangladesh, economic factors will dominate over the environmental and other social stresses in the transition pathways unless any visionary rigorous policy change occurs.

3.1 Renewable Awareness Assessment

The successful adoption of renewable energy sources is contingent upon the actions of policymakers since they possess the authority to formulate and enforce laws that facilitate and encourage the utilization of such sustainable energy alternatives (Gallagher, 2019). These policies may encompass various measures such as tax incentives, subsidies, and regulations aimed at enhancing the economic feasibility and appeal of renewable energy for both enterprises and individuals (Lam, 2020; Khan, 2017; Jobs, 2018). Policymakers assume a pivotal role in facilitating the shift towards renewable energy sources. There are several strategies via which politicians can facilitate and bolster this transition:

The formulation and execution of renewable goals is a viable approach for policymakers to adopt. These targets can be defined in several ways, either as a proportion of the overall energy production or as a specified quantity of installed renewable energy capacity. These targets establish a definitive trajectory and incentivize the allocation of resources towards the development and implementation of renewable energy technology.

The implementation of supportive policies can be achieved through the creation of incentivising measures by policymakers, which aim to promote the widespread use of renewable energy technologies. Financial incentives, such as tax credits or subsidies, may be employed to mitigate the financial burden associated with renewable energy projects (Jhang, 2021). Furthermore, legislators can enact policies that facilitate the integration of renewable energy sources into the current energy infrastructure.

To facilitate the advancement of research and development, policymakers possess the ability to dedicate financial resources towards the exploration and enhancement of renewable energy technology (Akhter, 2019). Policymakers have the potential to reduce prices and enhance the efficiency of renewable energy technology through their endorsement of innovation and achievements in this field.

Promoting international collaboration: Policymakers have the opportunity to engage in cooperative efforts with other nations, facilitating the exchange of valuable insights and expertise about policies on renewable energy (Jacobson, 2017). This collaboration has the potential to foster the establishment of worldwide norms and frameworks that promote the widespread adoption of renewable energy.

Policymakers possess the capacity to contribute to the elevation of public knowledge regarding the advantages of renewable energy and the imperative nature of its transition (Clarkson, 2020). Through the dissemination of knowledge and the rectification of any prevailing misunderstandings, policymakers can cultivate a favourable environment for the adoption of renewable energy policies and projects.

In general, policymakers possess the authority to establish a conducive atmosphere for the shift towards renewable energy through the establishment of objectives, implementation of supportive measures, facilitation of research endeavours, promotion of international collaboration, and enhancement of public consciousness. The acts undertaken by individuals play a pivotal role in expediting the widespread acceptance and implementation of renewable energy sources, ultimately leading to the attainment of a sustainable future (IRENA, 2021). Since policymakers are elected by the people, are are often assisted by professionals, their sentiment regarding their transition decisions is highly important to understand the probable transition pathways.

Renewable awareness has been assessed across several key role players in the policymaking of the energy arena. Alongside a wide online survey, the results were used to infer the willingness of people to go green in the energy sector, which may profoundly impact the central policymaking process. The survey mainly targeted potential people (e.g. Students, Politicians, Bureaucrats etc.) who are more likely to become involved in the decision-making processes now and future as the wider population in Bangladesh may not view carbonless energy as a priority. Therefore, the approach is crucial.

The major rationale of this open-ended interview is to gauge and identify the insights, understanding, awareness, plans, visions and knowledge about different aspects and prospects of renewable energy in Bangladesh among the influential stakeholders. In addition, it will try to extract the plans and socioeconomic and socio-political strategies considered by the government, political entities, and the non-governmental green energy agencies of Bangladesh regarding the penetration of green power. The questions were asked to the following entities from different interrelated sections.

The approval for conducting the survey and interview was given by the Faculty Ethics Committee, University of Southampton under the ID ERGO II 55042.

Table 13 List of interviewees and their roles in nexus to the study

Senior Leadership Role, Ministry of Power, Energy and Mineral Resources	**Senior Executive Role from Renewable Energy wing, Power Division)**	**Senior Executive/Decision-making Role Sustainable and Renewable Energy Development Authority (SREDA)**	**Senior Diplomat (Ministry of Foreign Affairs, Energy Wing)**	**Leading Executive Role, Bangladesh Power Grid Company Limited**	**Managing Director (Privately owned solar energy business firms in Bangladesh)**	**Senior official, Bangladesh Road Transport Authority**	**Energy Advisor, Advising role in national energy affairs**
1	2	3	4	5	6	7	8
Senior Political entity and administrative executive of the power-related issues	Administrative wing executive of the ministry, strongly and influentially connected to all policy planning, designing and implementation regarding renewable power	Administrative and implementing executive of sustainable energy research in Bangladesh (publicly funded)	Responsible for diplomatic communication about energy and power generation affairs	Administrative and implementing executive of power transmission in Bangladesh	Senior Manager of solar power system manufacturers and solar power producers in Bangladesh	Accountable for the permission of electric vehicle licensing, registration and regulations	Provide advice and recommendations in policy decisions

3.1.1 Interview Extractions

The principal rationale of this open-ended interview is to identify and gauge the depth of insights, awareness, plans, visions and knowledge about different aspects and prospects of renewable energy in Bangladesh among influential stakeholders. In addition, it will try to suggest the projects and socioeconomic and socio-political strategies considered by the government, political entities, and the non-governmental green energy agencies of Bangladesh regarding the penetration capacity of green power generation. The questions were asked to the following entities from different interrelated sectors. The extracts are tabulated in Appendix 10.1.

3.1.2 Survey responses

This online survey aims to assess the adoption and implementation of renewable awareness in Bangladesh. The survey was circulated among engineering students (Mechanical and Electrical), professionals, businesspeople, politicians, policymakers, bureaucrats, etc., who are more likely to be involved in the decision-making processes regarding energy and power issues at present and in the future in Bangladesh. The survey incorporated a Likert scale to measure the response psychometrically. Most of the participants are from the range between 31-40. It is because of the following:

- In the last ten years, many new engineers and administrators were recruited, appointed, and placed in Bangladesh's energy and power sector to meet the workforce demand for the rapid growth of that sector (Situ, 2019).
- Most of the newly appointed workforce were young (Situ, 2019) and are now between 31-40.

The survey request was circulated among the policy-making bureaucrats, political policymakers, engineers, and administrators already actively involved in government power and energy policy-related issues. It was also circulated among the Electrical and Mechanical engineering students from the top institutes (Through social media Pages) of Bangladesh who is likely to be willing for prestigious jobs in the public administrative service/power sector because of its prestigious features in Bangladesh.

The age range of 41-50 exerts the most significant influence over policy decisions. However, the younger participants would shortly replace them as well. Therefore, all of them are crucial in this survey.

Most of the respondents (51.9%) were implementors, organisers and managers of various activities in the generation, transmission, and distribution of power in Bangladesh. They include engineers, managers, project directors, monitoring authorities, policy analysts and formulators, project planners and administrators. Since the generalist policymakers depend heavily on them in all steps of policy formulation, enactment, implementation and evaluation, the roles seem significant for this survey and the research. The survey responses are tabulated and analysed in section 6.2.

3.1.3 Forecasting and Prediction

Depending on the projected variable trends mentioned in the previous sections, the study picks a non-linear modelling technique named generalised additive model (GAM) that can be extrapolated to a forecast model as well as saturating toward a logistic maximum (Demir et al, 2014). It is an extrapolation of the generalised linear model (GLM) framework, where the predictors are combined using individual additive functions to capture the non-linear relationships. GAMs have several advantages when it comes to forecasting, such as the ability to model nonlinear relationships between variables, handle missing data, and incorporate multiple predictors simultaneously. It can fit well to the short-term datasets where the independent variables have consistent growth patterns (Williams et al., 2018) which is pertinent to this study's context. They also allow for flexible modelling of complex data patterns, making them useful for a wide range of forecasting tasks.

GAM can handle time series data and make accurate predictions for future time points. One of the advantages of using GAMs is that they allow for non-linear relationships between predictors and the outcome variable, which can be useful for modelling time series data that may have non-linear trends or seasonal patterns. Additionally, GAMs can incorporate smoothing functions to model complex relationships between variables, which can improve the accuracy of predictions. GAM possesses superior capacity to others in regards (Ambya et al., 2020). The modelling settings in this study conform that kind of complexity among the variables. However, it is important to note that the accuracy of GAMs for forecasting future time points will depend on the quality and quantity of the data used to train the model, as well as the specific characteristics of the time series being modelled. The simulations tried to ensure the quality basing an array of accuracy measures.

The generalised additive logistic models (GALM) have demonstrated exceptional predictive accuracies, making them a potentially valuable tool for policymakers, implementation managers, and other stakeholders involved in decision-making related to state-issues management (Demir, Regression and Models, 2014; Geels *et al.*, 2017b; Ambya *et al.*, 2020; Schlosser *et al.*, 2020). This tool has the potential to enhance informed decision-making processes, leading to improved measures for policy performance management and capacities as well. The incorporation of several different kinds of variables is well managed in the forecasting scenarios as sophisticated multivariate nonlinear solver packages are widely available nowadays (e.g. MATLAB, R, Python). These features are highly pertinent to the sociotechnical capacity modelling and forecasting based on Bangladesh's Renewable transition. Therefore, the study decided to use it.

Non-linear Hybrid Generalised Additive Models (GAMs) have several advantages when it comes to forecasting:

Flexibility: GAMs are flexible models that can capture complex relationships between predictors and the response variable (Vaidya, 2020). They allow for non-linear relationships, and interactions, and can handle different types of predictors (continuous, categorical, etc.) at the same time.

Interpretability: In numerous social science and business contexts, the emphasis is frequently placed on elucidating the underlying causes of a phenomenon rather than only enhancing the predictive capabilities of the model regarding the occurrence of the event. This feature is highly pertinent for the modelling of the incumbent research. The presence of an interpretable model is of utmost importance in comprehending the way various components interact with the optimum outcome (Lam, 2020). The interpretability of the model holds significance in socioeconomic/sociotechnical/technoeconomic contexts that are subject to strict regulations, such as feasibility assessment processes. In scenarios where prioritising prediction accuracy over understanding the underlying mechanisms is paramount, the utilisation of an interpretable model can facilitate the identification and resolution of issues within complex models, as well as provide insights for refining feature engineering and data preparation techniques (Lam, 2020).

Handles missing data: GAMs can handle missing data effectively by using available information from other predictors (Wood, 2019). This makes them useful when dealing with real-world datasets that often have missing values.

Robustness: GAMs are robust to outliers and can handle noisy data well. They are less affected by extreme values compared to some other forecasting methods.

However, there are also some limitations or disadvantages to using GAMs for forecasting:

Computational complexity: GAMs can be computationally expensive, especially when dealing with large datasets or complex models. The estimation process may require more time and resources compared to simpler models. However, since a licensed MATLAB was accessible to the researcher the modelling was carried out successfully and fitted satisfactorily to the dataset.

Overfitting: Like any predictive model, GAMs can be prone to overfitting if not properly regularised or if the number of predictors is too large relative to the sample size. Regularization techniques such as cross-validation or shrinkage methods was used to mitigate this issue.

Assumption of linearity: Although GAMs allow for non-linear relationships, they still assume that the relationships are additive. If there are strong interactions between predictors, GAMs may not capture them accurately.

To address these limitations, the following were considered:

Simplify the model: If computational complexity is an issue, one can simplify the model by reducing the number of predictors or using dimensionality reduction techniques. Few of the variables were taken out of the list when seemed less influential[19] and embedded in other variables (Table 8).

Regularisation: Applying regularisation techniques like cross-validation or using a penalty term can help prevent overfitting and improve model performance (Shah, 2022). Fortunately, the variables considered in this study for Bangladeshi contexts had magnitudes with considerable consistency (Table 7). It happened mainly due to the consistent socioeconomic development in Bangladesh since last one and a half decade.

Consider alternative models: Depending on the specific requirements and characteristics of the data, it might be worth exploring other forecasting methods such as time series models (e.g., ARIMA or Prophet) or machine learning algorithms (e.g., random forests or neural networks). However, since GAM generated a considerably good fit for the dataset (5.1.13), other models were not considered.

Overall, while GAMs have several advantages for forecasting, it is important to consider their limitations and address them appropriately based on the specific context and requirements of the problem at hand.

[19] https://www.analyticsvidhya.com/blog/2023/09/understanding-generalized-additive-models-gams-a-comprehensive-guide/#h-advantages-and-disadvantages-of-gams

4 General Primary Estimations

4.1 100% Renewable Power for Bangladesh: A Prospect Analysis

The world of electrical power is currently moving through many transformational challenges regarding the paradigm shift necessitated by global sustainability and energy security issues that chronicle around economic, social, and environmental concerns (GEA, 2022). Climate change arising from GHG emissions is projected to affect the developing countries of Southeast Asia and Africa most severely shortly. The main actors behind the lion's share of global emissions have prompted them to green their power generation technologies to an extensive scale (Eckert, 2019). Nonetheless, unfortunately, developing countries are compelled to depend on and intensify their grips on conventional power generation technologies since they are comparatively cheaper but reliable and energy-dense (Williams, 2018). In this nexus, these countries suffer from policy dilemmas in their power sector and determine the optimum transition pathway. The following sections assessed the prospects of promoting 100% green electricity in Bangladesh by exploring the exploitable renewable potential and its usability.

4.1.1 Background:

The Sustainable Development Goals (SDGs), or the Global Goals, are a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity (UNDP, 2019).

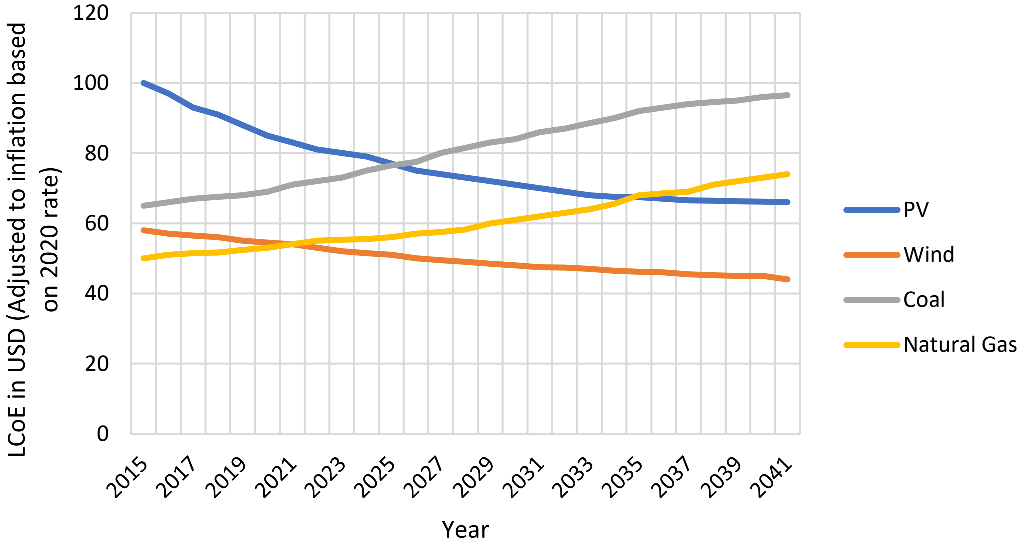


Figure 20: Forecast of levelised cost of electricity in future from different resources (New Energy Outlook, 2022)

The SDGs were enacted in January 2016 and will continue to guide UNDP policy and funding until 2030. Some 170 countries and territories around the globe agreed to adopt the goals in their national policies and development plans. Bangladesh has been very enthusiastic regarding SDGs and has effectively adopted the courses of action towards achieving those goals (GED, 2018).

SDG#7 states that, by 2030, to ensure universal access to affordable, reliable, and modern energy services and substantially increase the share of renewable energy in the global energy mix (UNDP, 2019). Adhering to that, Bangladesh has taken multiple initiatives in harnessing renewable power and using it to provide access to modern energy for millions of people to date. It has also set a target to install 10 GW generation capacity from renewable resources by 2041. In the meantime, policymakers also understand that there may be a dramatic fall in the renewable power price in the future that may surpass the carbon-emitting systems regarding economic efficiency by the next decade (Figure 20). If the country is delayed in exploiting the relative advantage of such green systems at that time, it may result in a transition shock that will severely affect the overall economy, as energy has multiplier effects on almost all socioeconomic indices (Farag & Komendantova, 2014). Therefore, the government seeks to determine the optimum pro-green policy decisions through periodic adjustments and amendments in the future. This section provides an assessment of the maximum extractable renewable power within the territory of Bangladesh, along with some pragmatic observations.

4.1.2 The Demand Scenario

The utility electricity sector in Bangladesh has one national grid with an installed capacity of over 25 GW as of 2023, and according to the Bangladesh Power Development Board, 100 per cent of the population had been provided with access to electricity (BPDB, 2023).

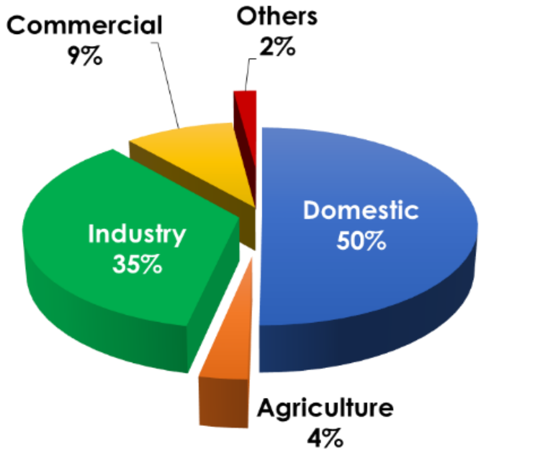


Figure 21 Power use by sector in Bangladesh in 2017 (PSMP, 2018)

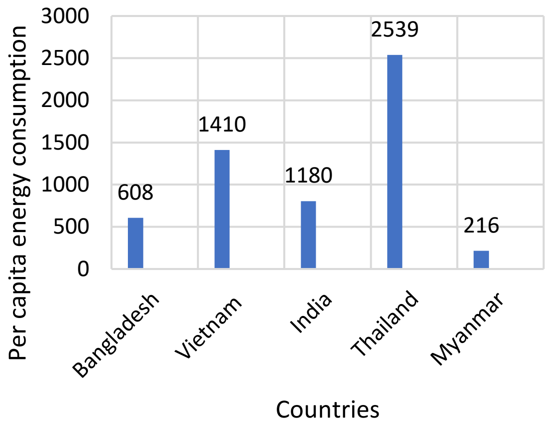


Figure 22 Per Capita Electricity Consumption comparison among some neighbouring states of Bangladesh in kWh (WB, 2019)

However, the same source confirms that Bangladesh's electricity consumption per capita, 608 kWh per annum, is still low[20]. One of the major reasons behind this poor per capita electricity consumption is the installation of very small solar home systems supplying merely a very small level of power among more than six million rural households and counting them to have power access similar to those connected to the national grid (Molla, 2017). Other reasons may include frequent power outages from outdated power plants and transmission systems, poor affordability, and mostly non-industrial use of electricity (Moazzem, 2019).

[20]http://www.powerdivision.gov.bd

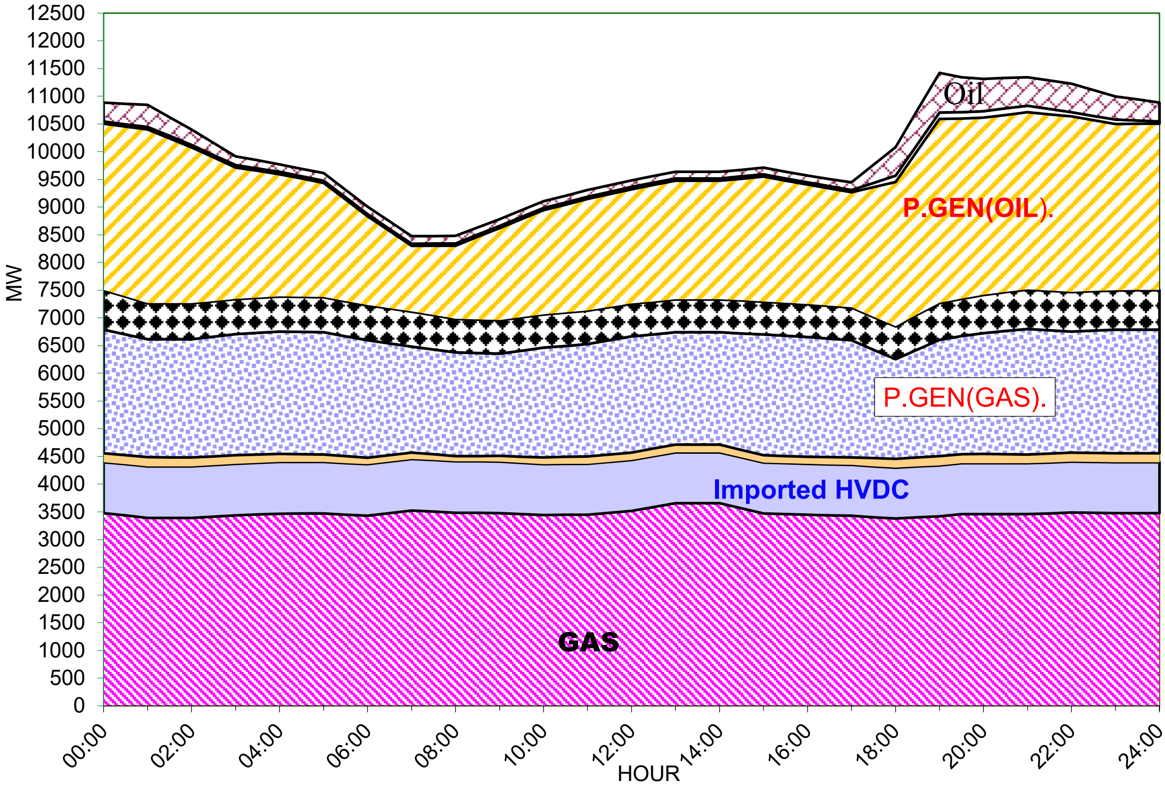


Figure 23: Energy Mix for Power Generation on 22/09/2020 (PGCB, Bangladesh, 2020)

Natural gas is a large share of the electricity generation mix in Bangladesh. Respectively other sources like oil, coal, hydro, renewable energy, and imported power from India (HVDC) are contributing to generating electrical power (Figure 23). Enunciating a roadmap in the current government's electoral manifesto, Bangladesh takes up an ambitious development venture to become a developed nation by 2041 (Vision2041, 2013)

Table 14: Installed Capacity of BPDB Power Plants as on January 2023 (BPDB, 2023)

Fuel Type	Capacity (Unit)	Total (%)
Coal	2692 MW	11.46 %
Gas	11522 MW	49.07 %
HFO	6278 MW	26.74 %
HSD	1341 MW	5.71 %
Hydro	230 MW	0.98 %
Imported	1160 MW	4.94 %
Solar	559 MW	4.1 %
Total	25482 MW	100 %

Bangladesh Power Development Board (BPDB) is a statutory body created on May 1, 1972, by Presidential Order No. 59 after the bifurcation of the erstwhile Bangladesh Water and Power Development Authority. BPDB had started its operation with a generation capacity of only 500 MW. In its 50 years of service, the country's installed capacity increased to 25,482 MW at the end of FY 2022 (BPDB, 2023).

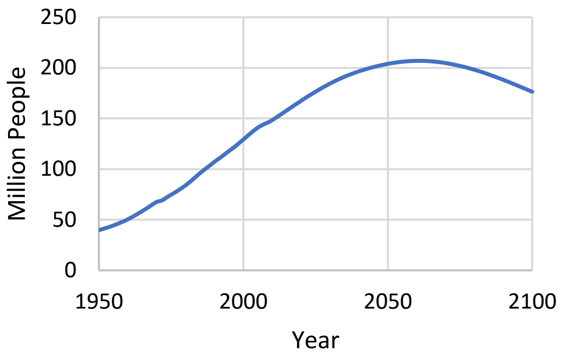


Figure 24 Population Growth Projection of Bangladesh (WPR, 2017)

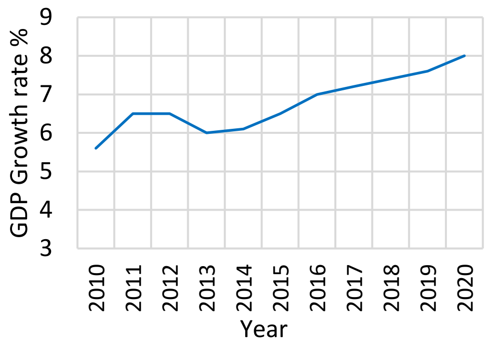


Figure 25 GDP growth rate trend (Seventh Fifth Year Plan, Planning Commission, Bangladesh)

In the latest Power System Master Plan, the Power Division of Bangladesh projected the future power demand based on projected economic development (Figure 26), population growth (Figure 24) and sector-wise future power consumption (BPDB, 2023).

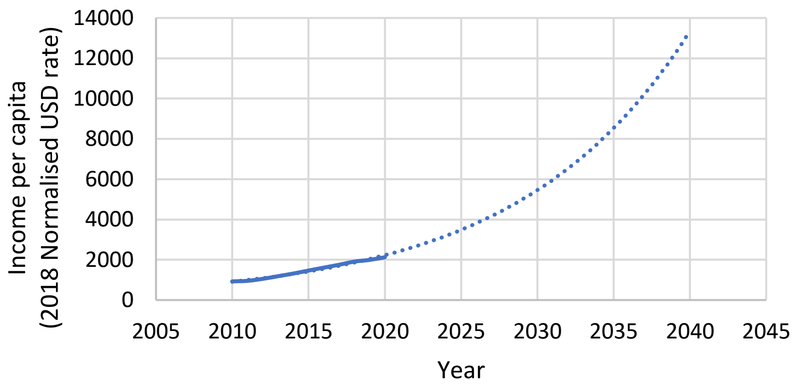


Figure 26 Income Growth projection for Bangladesh according to Vision 2041 (PC, 2020)

Bangladesh has made remarkable progress in reducing poverty, supported by sustained economic growth. Based on the international poverty line of $1.90 (using purchasing power parity exchange rate) daily, it reduced poverty from 44.2 per cent in 1991 to 14.8 per cent in 2016/17 (WorldBank, 2019). According to the Planning Commission of Bangladesh, Bangladesh aspires to cross per capita income of 14000 USD by 2040 (Figure 26), adjusting the inflation at the normalised rate of 2018 (PC, 2020).

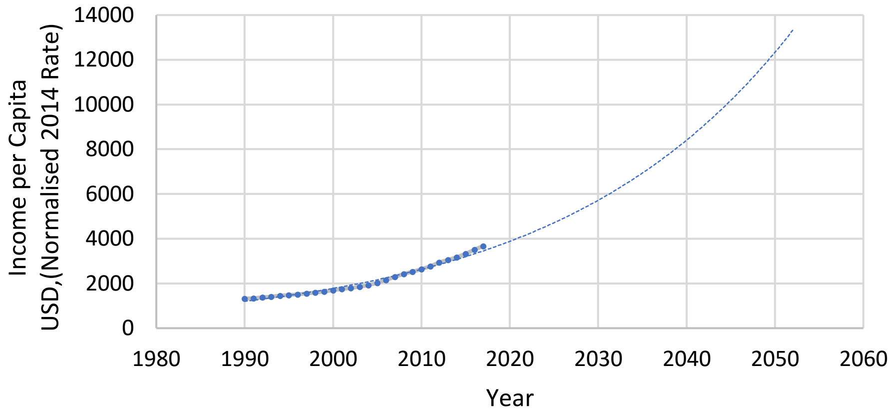


Figure 27: Income Growth Projection for Bangladesh by the World Bank (WB,2019)

According to the projection of the World Bank (Figure 27), the anticipated income per capita is a little less, like 11000 USD per capita at the same normalized rate if the rise retains its consistency (WB, 2019).

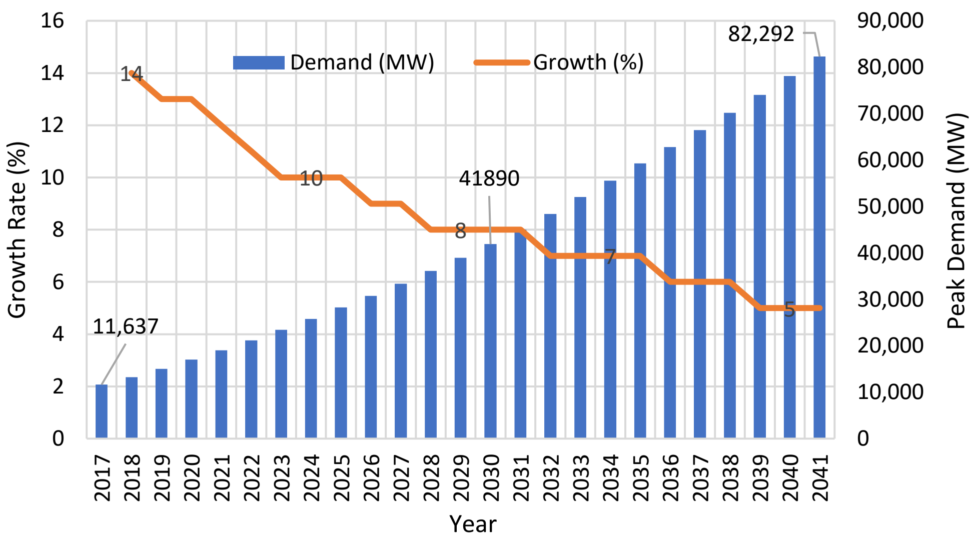


Figure 28 Year-wise Peak Power Demand Forecast and Growth Rate (Power System Master Plan, Power Division, Bangladesh (2016))

Bangladesh's economy has seen steady growth since independence was declared in 1971. GDP per capita has been steadily expanding since the 1990s when the ready-made garments (RMG) sector emerged as a major export industry for the country. GDP annual growth rate during the Sixth Five-Year Plan from 2011 to 2015 averaged 6.3%. According to the Seventh Five-Year Plan formulated by the Government of Bangladesh, the average GDP growth rate from 2016 to 2020 is expected to reach 7.4%.

Because of the situation in Bangladesh, whereby rolling blackouts have been used to bypass power shortages at peak hours, the recorded maximum power consumption does not reflect potential power demand. Therefore, an accurate forecast of the maximum demand, including the potential demand, requires a theoretical estimation of load curves from the daily operational data with particular attention to the characteristics of the seasonal changes in the daily load curve and the frequency and duration of rolling blackouts. Because rolling blackouts have been relatively rare on weekends and holidays in the winter (between November and January), a daily load curve (Figure 29) gives an actual peak load (at the hours of the peak power consumption for lighting) that is quite accurate. A daily load curve in the summer estimates the base and intermediate loads close to the recorded values (Figure 30).

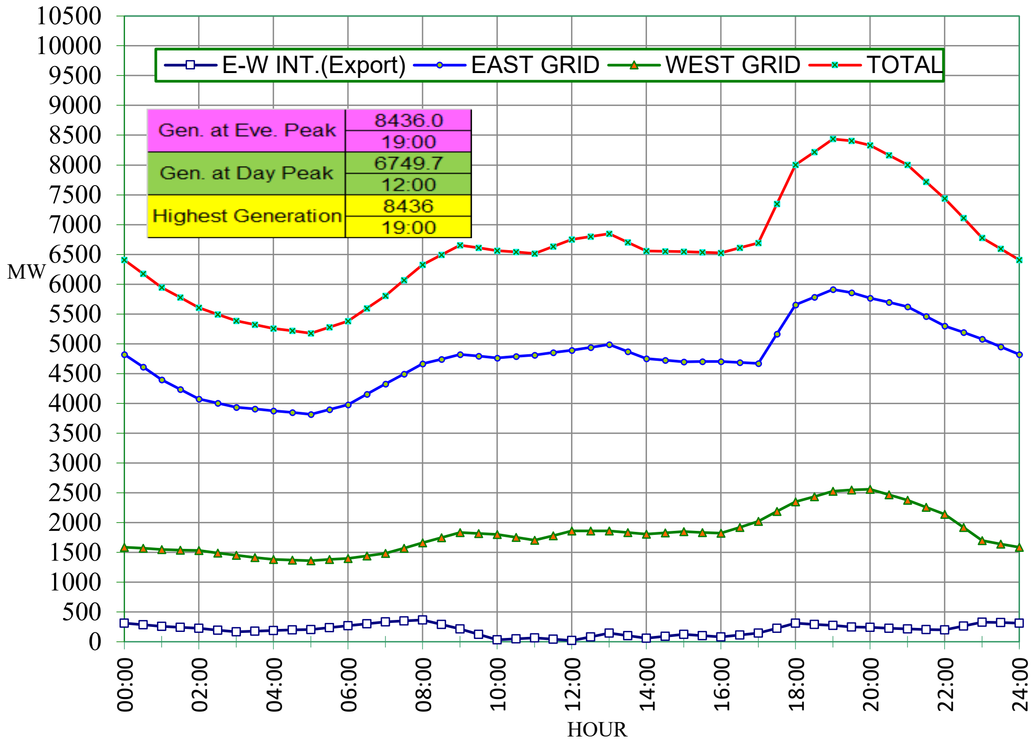


Figure 29 Typical Demand Curve, Bangladesh, Working Day Winter, 2 January 2020 (PGCB, 2020)

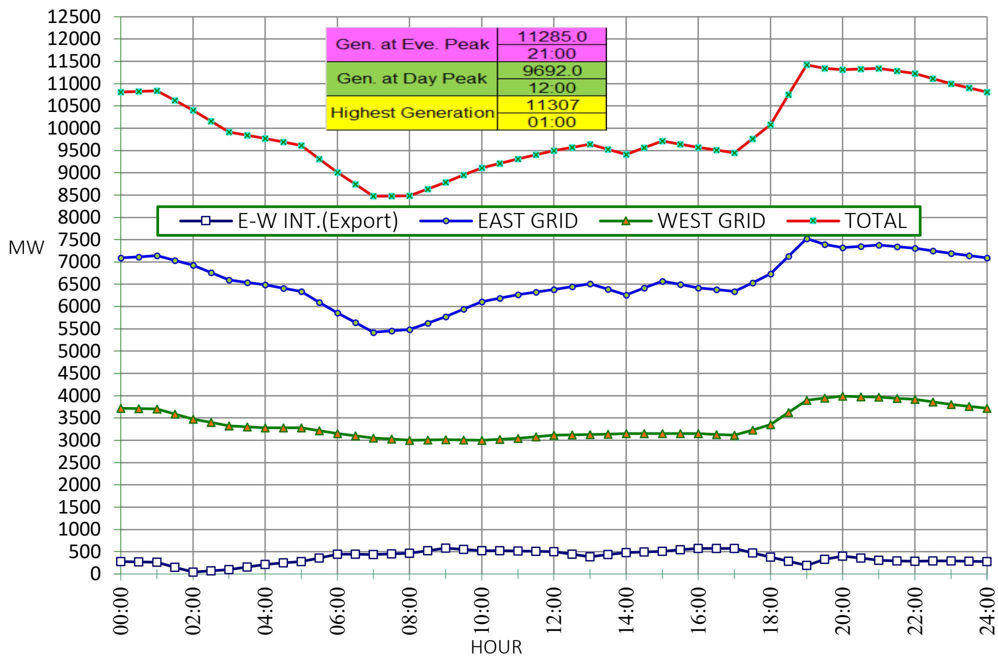


Figure 30 Typical Demand Curve, Bangladesh, Working Day Summer, 2020 (PGCB, 2020)

Global warming is rapidly shortening the winter period in Bangladesh, making the country monoseasonal (Khan *et al.*, 2020). A daily load curve provides an actual peak load that is pretty precise (during the hours of the peak power usage for lighting) because rolling blackouts have been relatively uncommon on weekends and holidays throughout the winter (between November and January). During the summer, a daily load curve estimates the base and intermediate loads relatively close to the recorded values (1st curve in Figure 31). During winter, there is a sudden surge in demand at midnight as all the electrical irrigation pumps are turned on due to lower tariff rates (subsidised). That winter irrigation surge surpasses the summer night surges (2nd curve in Figure 31). As a result, to capture that surge, a composite daily load curve that represents the peak power demand was created by starting with the daily load curve in the summer and replacing a portion of the peak hours with the same portion of the daily load curve in the winter, as shown in the figure below (3rd curve in Figure 31). For example, the peak power demand in FY 2014, which was used as the baseline for the peak demand forecast, was set at 8,039 MW by adding the base and intermediate load in the summer (5,487 MW and 1,043 MW, respectively) and the peak load in the winter (1,811 MW) recorded in FY 2015. It resulted in 8,039 MW required to meet the peak power demand in FY 2014. The same methodology was used to estimate 8,921 MW for the peak power demand during the fiscal year 2016. This number was utilised as the reference value in the peak power demand prediction (Power Division, 2016).

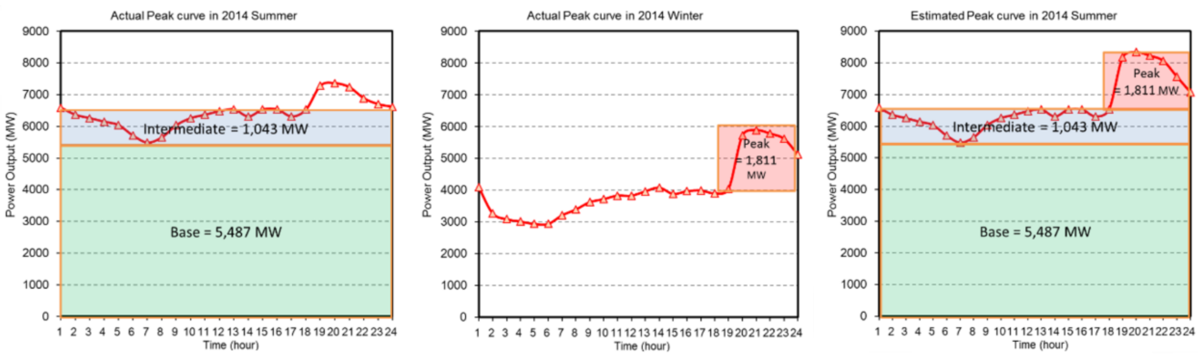


Figure 31 Estimated Composite Daily Load Curve in the Summer in Bangladesh (2014) (Curves taken from PGCB, 2018)

Bangladesh is still planning its power generation from carbon-emitting systems because of its limited affordability and comparatively poorer efficiency and reliability of renewable systems. According to revisited PSMP 2016, the peak power demand by 2041 of Bangladesh will be approximately 82 GW which leads to an amount of 400-425 TWh (Figure 32) yearly energy consumption in keeping with the aggregated daily demand pattern. Applying energy conservation and efficiency policy, this amount may be curbed by 65-70 GW (PSMP, 2018).

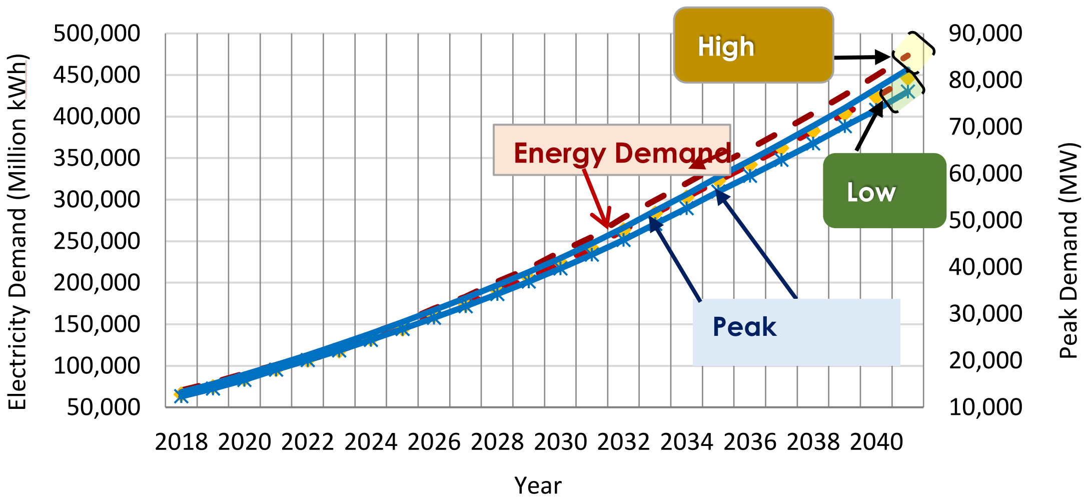


Figure 32 Projected Yearly Peak Demand (MW) and Electricity Demand (mkWh) in Bangladesh (PSMP, 2016)

However, it has recently realised the necessity of planning its sustainable energy transition as the energy future would be strongly heading for green transformation (INDC, 2015).

4.1.3 Consideration of the future use of Electric Vehicles

One stark limitation of this demand forecast is that it did not consider the rise in the use of electric vehicles in the future. To implement SDG, global EV sales will occupy a significant portion of the total transport domain (Figure 33) (IEA, 2019). Nevertheless, electric vehicles (EVs) will replace internal combustion engines by 2040 in most developed countries doubling the electricity demand (UoO, 2018).

Therefore, if Bangladesh becomes a developed country by 2041 or beyond, it is more likely to have many electric vehicles that will significantly raise the total power demand.

While electricity is essential for electric vehicle penetration, it is unlikely to introduce a barrier to diffusion unless policy and regulation are acutely formulated or implemented (UoO, 2018). Unsurprisingly, recently Bangladesh government has enacted the licensing of electric vehicles, and some companies have started to market EVs in Bangladesh (Islam, 2019). Moreover, the number of battery-driven three-wheelers on Bangladeshi roads surpassed a million, becoming an influential disruptor in the power grid already (Karmaker, et al., 2018).

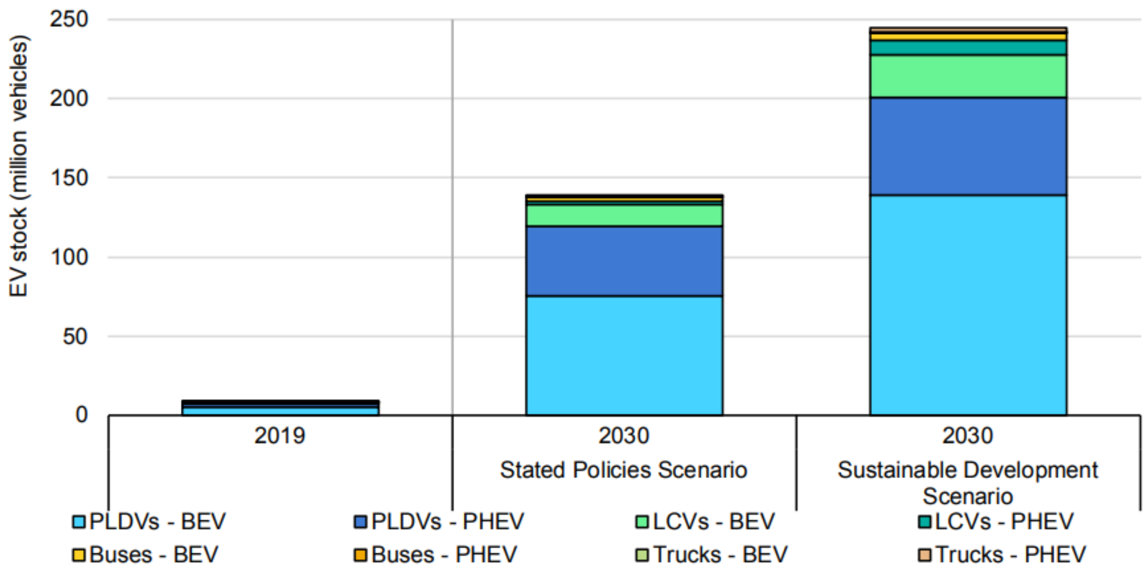


Figure 33 Global electric vehicle stock by scenario, 2019 and 2030; PLDVs = passenger light-duty vehicles; LCVs = light commercial vehicles; BEV = battery electric vehicle; PHEV= plug-in hybrid electric vehicle (IEA, 2019).

Though currently a niche market, these battery-driven three-wheelers are the proven predecessor of the future EV landscape in Bangladesh. A developed country like Malaysia has a development pattern and trends to Bangladesh. Using numerical analogy and assuming the future carbon-free transport and having 300 cars per 1000 people by 2041, the power demand may be affected significantly by this increased load from car charging. In that case, the aggregated yearly consumption is around 110 TWh (electrical energy) for 60 million cars. With an estimated travel distance of 100 kilometres with 15 kWh of energy, while Bangladesh's average car travels 20.38 Km a day[21], suppose one electric car consumes 3.2 kWh (To run 20.38 km in the case of Nissan Leaf daily[22]). Therefore, an additional lump of 25 TWh of electricity will be required to be added to the total energy demand. With a capacity factor of 30%, this amount may be harnessed by adding 41 GW of

[21] https://www.numbeo.com/traffic/in/Dhaka
[22] https://ev-database.org/car/1106/Nissan-Leaf

peak power generation. Therefore, considering the future use of electric vehicles will significantly affect the demand profile reflected in the Power System Master Plans.

4.1.4 Consideration of the seasonality and variance in demand pattern

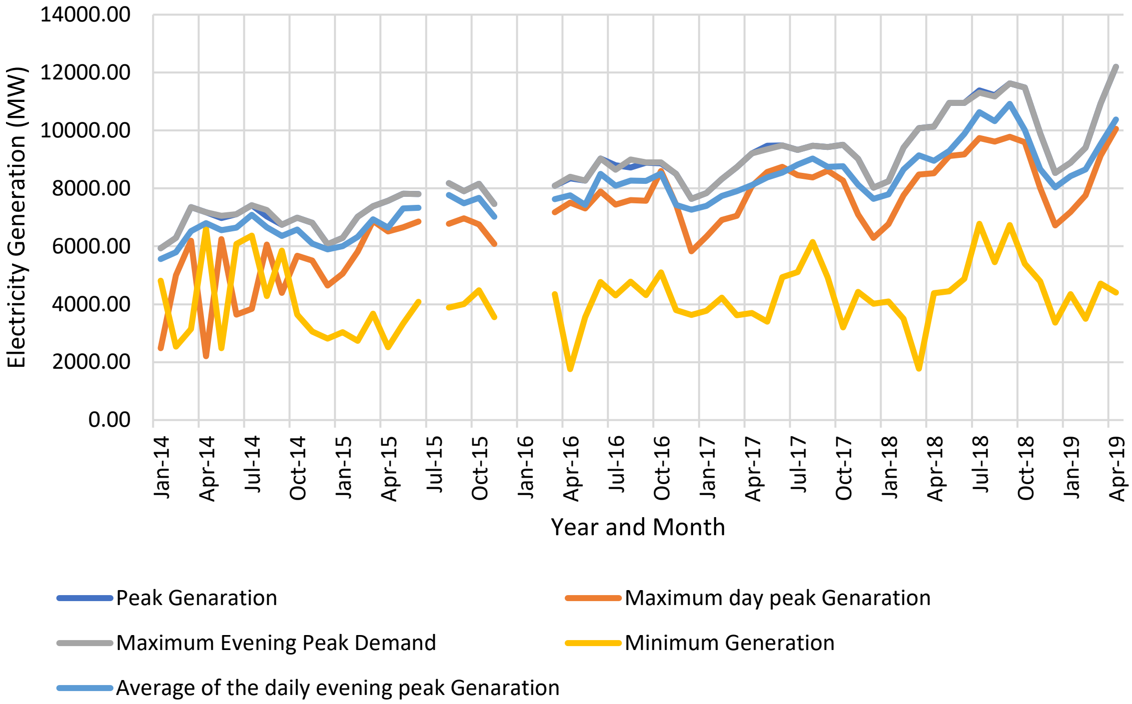


Figure 34: Bangladesh power Generation Scenario (January 2014- April 2019) (Data Source: PGCB Bangladesh)

Figure 34 plots the monthly peak power generation, maximum day peak generation, maximum evening peak demand, minimum generation, and an average evening peak generation. It denotes the cyclic amplification of the indices due to the rising economy and seasonality. The following table (Table 15 Monthly Mean Generation and corresponding Cooling Degree Days from May 2016 to May 2019 in Bangladesh (Data Source: PGCB Bangladesh)) gives the Monthly Mean Generation and corresponding Cooling Degree Days from May 2016 to May 2019 in Bangladesh (Data Source: PGCB Bangladesh).

Table 15 Monthly Mean Generation and corresponding Cooling Degree Days from May 2016 to May 2019 in Bangladesh (Data Source: PGCB Bangladesh)

Month	Mean Generation (MW)	CDD	GW/CDD	GW/CDD (above CDD= 200)	cold months	hot months
01/05/2016	7433.1	198	37.54091			
01/06/2016	8503.2	230	36.97043	36.97043		8503.2
01/07/2016	8093.68	209	38.72574	38.72574		8093.68
01/08/2016	8270.32	226	36.59434	36.59434		8270.32
01/09/2016	8263.63	202	40.90906	40.90906		8263.63
01/10/2016	8515.65	205	41.53976	41.53976		8515.65
01/11/2016	7425.63	96	77.35031		7425.63	
01/12/2016	7267.06	43	169.0014		7267.06	
01/01/2017	7400.16	28	264.2914		7400.16	
01/02/2017	7736.32	68	113.7694		7736.32	

Month	Mean Generation (MW)	CDD	GW/CDD	GW/CDD (above CDD= 200)	cold months	hot months
01/03/2017	7902.45	105	75.26143			
01/04/2017	8109.42	177	45.81593			
01/05/2017	8379.77	233	35.96468	35.96468		8379.77
01/06/2017	8545.53	207	41.28275	41.28275		8545.53
01/07/2017	8818.16	203	43.43921	43.43921		8818.16
01/08/2017	9035.13	219	41.2563	41.2563		9035.13
01/09/2017	8743.39	217	40.29212	40.29212		
01/10/2017	8769.23	182	48.18258			
01/11/2017	8127.47	99	82.09566		8127.47	
01/12/2017	7644.48	38	201.1705		7644.48	
01/01/2018	7796.06	14	556.8614		7796.06	
01/02/2018	8652.54	70	123.6077		8652.54	
01/03/2018	9137.13	173	52.81578			
01/04/2018	8951.2	162	55.25432			
01/05/2018	9298.03	170	54.69429			
01/06/2018	9879.5	218	45.31881	45.31881		9879.5
01/07/2018	10632.13	226	47.04482	47.04482		10632.13
01/08/2018	10324.52	242	42.66331	42.66331		10324.52
01/09/2018	10919.57	240	45.49821	45.49821		10919.57
01/10/2018	10017.1	177	56.59379			
01/11/2018	8671.83	97	89.40031		8671.83	
01/12/2018	8032.26	32	251.0081		8032.26	
01/01/2019	8425.06	30	280.8353		8425.06	
01/02/2019	8652.54	48	180.2613		8652.54	
01/03/2019	9524.16	136	70.03059			
01/04/2019	10379.33	195	53.22733			

The power demand pattern in Bangladesh is significantly influenced by seasonal demand shifting due to the massive increase in cooling load during much longer arrays of summer days compared to colder days (Figure 31). Observing the Cooling Degree Days throughout three consecutive years, it can be inferred that the demand varies majorly due to household cooling loads or non-industrial use.

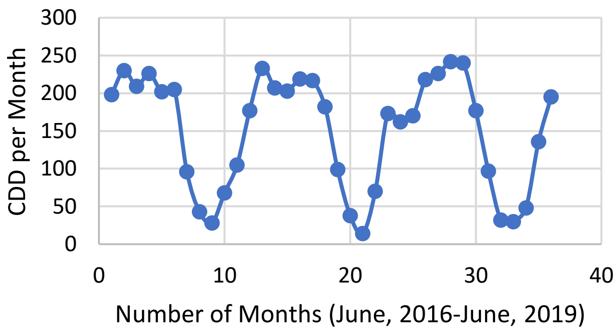


Figure 35: Seasonal Cyclic Variability of CDD for three years or 36 months (01/05/16-01/04/2019), 0-36 show intervals every month

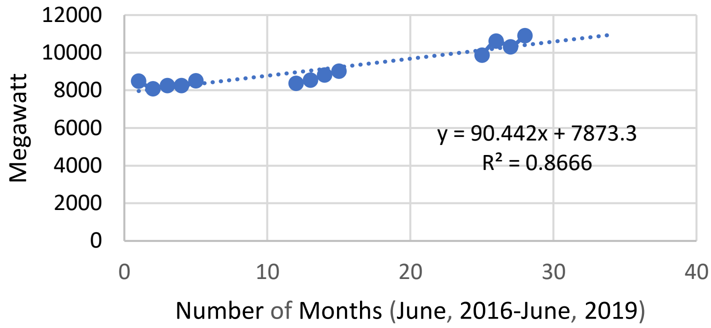


Figure 36: Summer Month Peak Demand (01/05/16-01/04/2019), 0-36 show intervals every month

Summer month demand peaks also exhibit a yearly linear rise (Figure 36) that denotes the progressive rise in energy access and generation capacity, probably triggered by the consumers' economic development and the suppliers' increasing capacity.

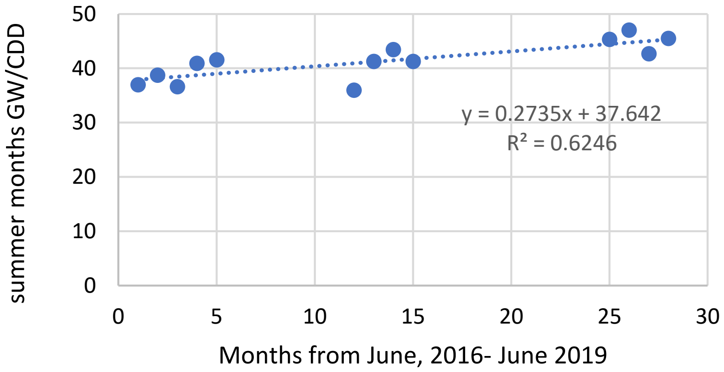


Figure 37: Demand during Summer Months (GW/CDD, CDD>200, (01/05/16-01/04/2019))

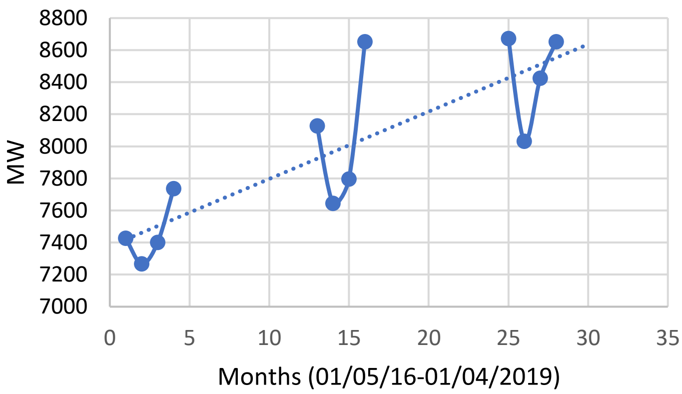


Figure 38: Cold Month Demand (01/05/16-01/04/2019)

Assessment between the effect of hot months (Figure 37) and cold months (Figure 38) on-demand profile implies that the rational gap between them is reducing yearly. The effects of global warming or climate change may have caused this situation, according to expert opinions. For the past few years, the winter chapter of Bangladesh has been shrinking, arriving late, and living short; what experts suspect is climate-related changes and abuse of natural resources (Chakrabortty, 2017). A study analysed the sales data of air conditioners in Bangladesh in the last six years and said that approximately 2.8 million air conditioners are used throughout the country (ProthomAlo, 2022). Additionally, some scholars blame the abuse of natural resources, establishments on wetlands and shrinking water bodies for the abnormality (Chakrabortty, 2017). That is why the cold month demands are rising more rapidly than the summer month demands, as presumably, days are getting fewer when fans and other air-cooling appliances (air conditioners) are turned off.

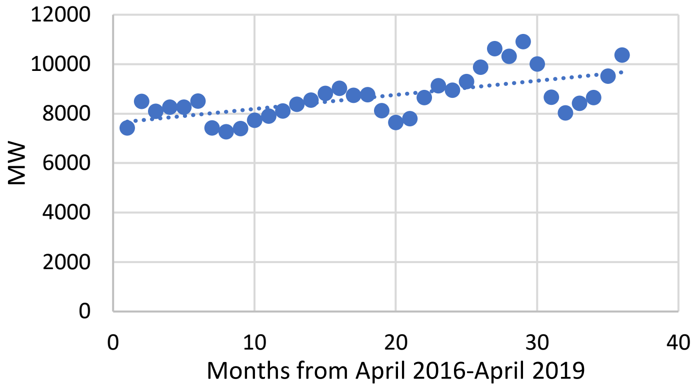


Figure 39: The cyclic amplification of peak demand (01/05/16-01/04/2019)

A preliminary seasonality modelling in MatLab predicted a rising sinusoidal function fitting the data (Figure 40). Since the rise exhibited linear and cyclic fashion, the model was fitted to the curve,

y=30(x-2)*sin(0.5(x-2))+b(x-2)+c

The curve can be fitted more precisely with an asymptotic trend, as the demand will be saturated at some point in the future. The later phase of the research incorporated those considerations.

y = C+ L./(1+exp(-k*(x-x0))) + A.*sin(B*x)

Logistically, => $y = a + \frac{L}{1+b*e^{c*x}}$

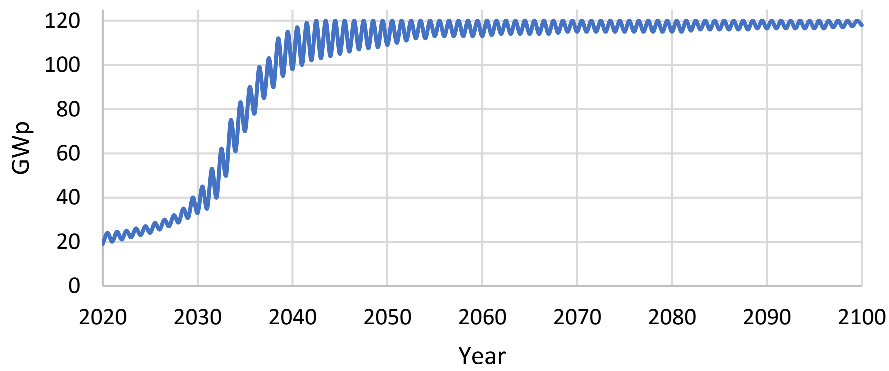


Figure 40: Logistic-Periodic Peak Power Demand Seasonality Modelling in MATLAB (Demand GW vs Years)

Figure 40 expresses the future trend in the power demand of Bangladesh based on population and economic affordability reinforced with the consideration of innovative introduction and promotion of electric vehicles and seasonality. However, Bangladesh is becoming a monoseasonal country with overwhelming global warming experiencing shorter and warmer winters (Standard, 2019). Taking this into account, the latter seasonal variance was dampened to 10% of initial variation (Future of Climate Change: United States Environmental Protection Agency[23]). That is why it looks tapered later.

Over the last two decades, Bangladesh is experiencing a rapid rise in annual power demand due to increasing socioeconomic growth. The rapid expansion of economic activities, industrialization, and subsequent rise in economic affordability, coupled with population growth, are the main driving forces behind the rise in demand. The geolocation and tropical climatic conditions also strongly influence the demand fluctuations around the year. Hence, there is a need to provide a robust forecast of the power demand to establish rationales for policy and strategies geared to meet such demand. Moreover, a precise demand profile is pivotal to plan on the selection, design, and implementation of the optimum renewable transition strategies, which seem indispensable soon. The available models lack seasonality consideration, and the future use of electric vehicles can substantially increase demand. This study establishes a modelling approach to quantify the impact of such socioeconomic growth on the upcoming power needs of the country. The research uses a logistic regression approach fitted to the hourly demand data of the past four years and future energy demand in Bangladesh whilst being commensurate with future country population growth and affordability forecast. The work also considers the influence of the promising rise in the use of electric vehicles in the future, along with implementable energy efficiency and conservation strategies. In the analysis, some inferences were made from existing socioeconomic scenarios from contemporary but comparable countries to predict the future power demand in Bangladesh. Amending the previously done studies, the updated results show an annual cyclic amplification in demand growth that will plateau to around an annual electrical energy demand of around 400-450 TWh. Such findings may be useful to guide the policymakers and other stakeholders regarding the future power sector characteristics, develop policies and strategies to meet the future energy demands in Bangladesh and comprehend the challenges of green transitions.

4.1.5 Errors in the estimations

Short-term errors in daily operational forecasts and long-term errors in annual development forecasts are the two forms of errors in the demand forecast. A short-term error may be a deviation between actual and forecasted daily demand for the next day's operation planning (PSMP, 2016). An example is the unanticipated change in demand caused by an error in weather forecasting. Since short-term deviations cannot be compensated for by the abrupt development of additional supply capacity, reserve capacity must be prepared for such occurrences. On the other hand, errors deriving from a long-term (e.g., a decade-long term) demand forecast can be adapted to some extent in the annual rolling development plans. Therefore, the supply reserve margin is not required to account for the long-term deviation. However, the annual rolling plan cannot alter long-term power system development plans, necessitating a certain reserve margin level to account for the long-term variation (Power Division, 2016).

[23] https://climatechange.chicago.gov/climate-change-science/future-climate-change

5 Socioeconomic Capacity Modelling for Renewable Transition in Bangladesh: Simulation and Analyses

Energy System Transition Models deliver the conceptual idea of paradigm shifts in power generation systems driven by multifaceted sociotechnical factors and parameters. It enhances the capacity to make rational and precise inferences for planning and implementing transitional energy-related agendas, extending from local to global contexts. In the nexus to assessing the extent of influences of different socioeconomic and technical factors and parameters (namely variables) on this renewable power transition, the study decided to establish a model to forecast Bangladesh's future sociotechnical capacity in transitioning towards renewable power. The model aims to support policymakers and planners in making informed decisions and prioritising implementation strategies according to their escalating socioeconomic plus technical capacities. Past literature was searched for the optimum modelling technique for Bangladesh's renewable transition, noting that the countries whose sociotechnical and socioeconomic settings are considerably distinctive from many others. This study then proposed formulating and simulating a novel mathematical model using the combination of vector autoregression and logistic, nonlinear technique incorporating several independent and influential variables to obtain a plausible forecast of the probable transition. A multiple equation-based logistic-function regression model was coded in MATLAB based on the past several years' trends of the rationally chosen variables. Forecasting various future transition pathways was undertaken by varying the magnitudes of the variables to different extents to detect and determine each variable's individual and combined impact on the transition towards 100% green power in Bangladesh.

The model simulation exhibits the effects and extent of the impact of various influencing factors on the green transition scenarios. The model gives an insight into how the renewable share in the energy mix should be progressively elevated according to factors like the future escalation in financial affordability, land availability or the technical advancement of the overall efficiency of the suitable renewable systems and other factors for the country. The order may be rearranged or modified with further iterations and the latest data available during future research. For example, foreign grants have contributed majorly to date, but they will not be as available in the future due to the graduating self-affordability. The findings inculcated a much higher capacity level for renewables, even according to Bangladesh's current and upcoming sociotechnical capacity. Furthermore, some of the results of the simulations suggest that Bangladesh may have to depend upon its neighbouring countries to be 100% powered by renewables.

The model comprised several independent variables like income per capita, LCoE from fossil fuel and renewables, system efficiency, green power import, foreign grants and aids, land availability, carbon taxation etc. It is assumed that these factors influence the renewable power generation in Bangladesh as a hypothesis. In Matlab, the year-wise numerical data of each of the variables were fitted into trendlines separately and then all of them were plugged in the logistic GAM transition model function (Equation 7,8,9, page 68). The values of the model’s coefficients were determined through using the VAR solver (in Matlab) for solving multiple equations constructed on time-series datasets. The goodness of fit was measured and optimised over conducting multiple iterations of searching the optimum set of “k” values through insertion of different search regions by changing the upper and lower limits (Table 10). Since Matlab today has commendable capacity to perform large, complicated calculations for solving the sets of non-linear equations, wide ranges for setting the upper and lower boundaries were used. For each iteration with the changes in the set boundaries and limits, the goodness of fit statistics changed accordingly. Following several intuitive and tacit iterations, when the R-square value turned larger than at least 0.8 (Most of the cases it was near to 0.9), the simulation was considered for keeping and analysing in the thesis. With an acceptable goodness of fit, the coefficients were determined and inserted into the model equation to construct it. Since, all the independent variables were time-dependent, the transition capacity (dependent variable) is also a function of time. The modelling is coded on Matlab in such a way that both the dependent and independent functions are expressed in temporal forms (function of time). Then they were interlinked in putting altogether in the logistic GAM model function. Therefore, varying the magnitudes of the influencing variables throughout any timespan (here up to the year 2100), the extrapolation would be operated in a multivariate manner whenever necessary to demonstrate any particularised simulated scenario. Here is an example to clarify this.

The researcher sets the upper and lower boundary to search for the k values in equation 9 like the following:
lb = [0 0 -90 0 0 0 0 0 -30 -500];
ub = [90 90 0 90 90 90 90 90 0 500];

It gives solution set of k values like the following:

k = 0.0011, 0.0030, -0.0002, 0.0072, 0.1106, 0.0051, 0.0012, 0.0003, -0.0000, 6.6560

Here, the R-square was 0.52

If the search boundaries are changed into following:
lb = [-100 -1000 -900 -100 -100 0 0 -1000 -30 -500];
ub = [15000 900 0 900 900 900 900 900 10000 500];

It gives solution set of k values like the following:
k = 0.0021, 0.0035, -0.0000034, 0.0075, 0.2106, 0.00571, 0.00001, 0.00063, -0.00001, 11.673

And the R-square becomes 0.81

It means the second iteration brings better fit. This criterion was used to improve the goodness of fit during the simulations. Each of the simulations were carried out towards the most possible convergence direction based on the features of the goodness of fit mentioned earlier.

5.1.1 Renewable generation capacity Prediction for Bangladesh: Simulated Outcomes

This section demonstrates various simulated results to display the maximum possible capacity of renewable power generation as the output variable based on simulating eight independent variables.

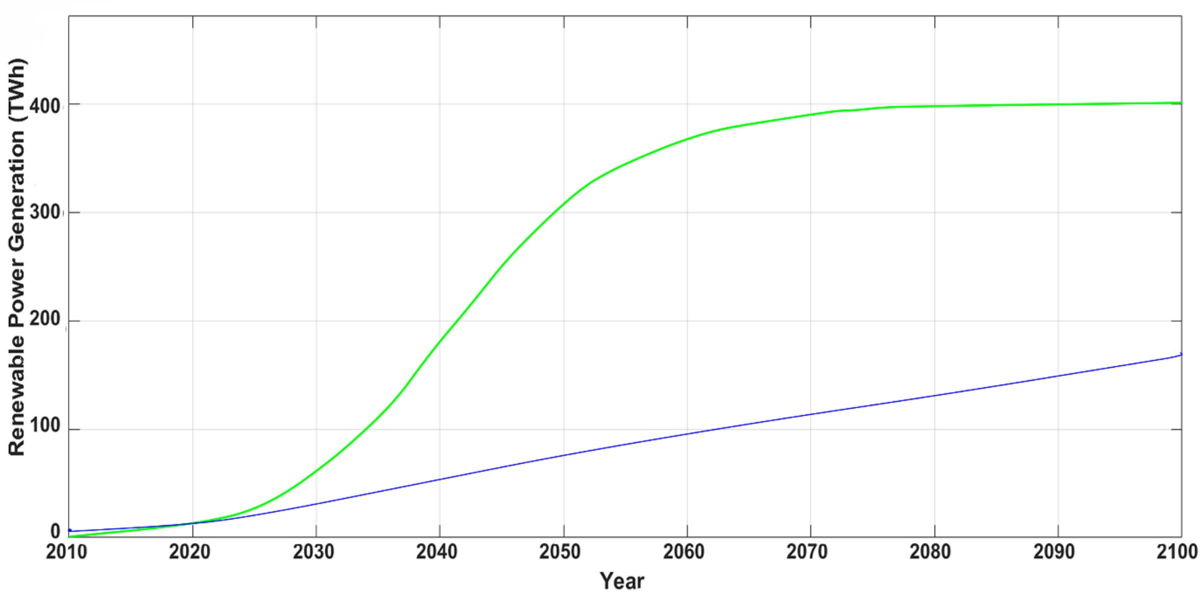


Figure 41 Renewable generation capacity Prediction for Bangladesh from 2020-2100 (Following Variables' Projections —— and Business as Usual (Linear extrapolation) ——)

Figure 41 suggests the renewable power generation trends in two ways. The green line indicates the modelled logistic growth of green power generation based on the nine variables' predicted changes. It suggests reaching 100% renewable power in Bangladesh may take up to 2080 or beyond if the influential factors move as the rationalised predictions. If the current trend of renewable escalation occurs in simple linear growth as per the last ten years, by 2100, it will barely produce 150 TWh. It clearly implies that the factors must retain their rational growth patterns (not necessarily always linear) or changes to ascertain the affordability of renewable Transition in Bangladesh. Any point on the green line presents how much renewable power Bangladesh can feasibly generate at a particular time. For example, by 2030, Bangladesh may gain the socioeconomic capacity to afford 80 TWh of renewable power (Green line in Figure 41).

5.1.2 Impact of Income Growth Changes on Transition

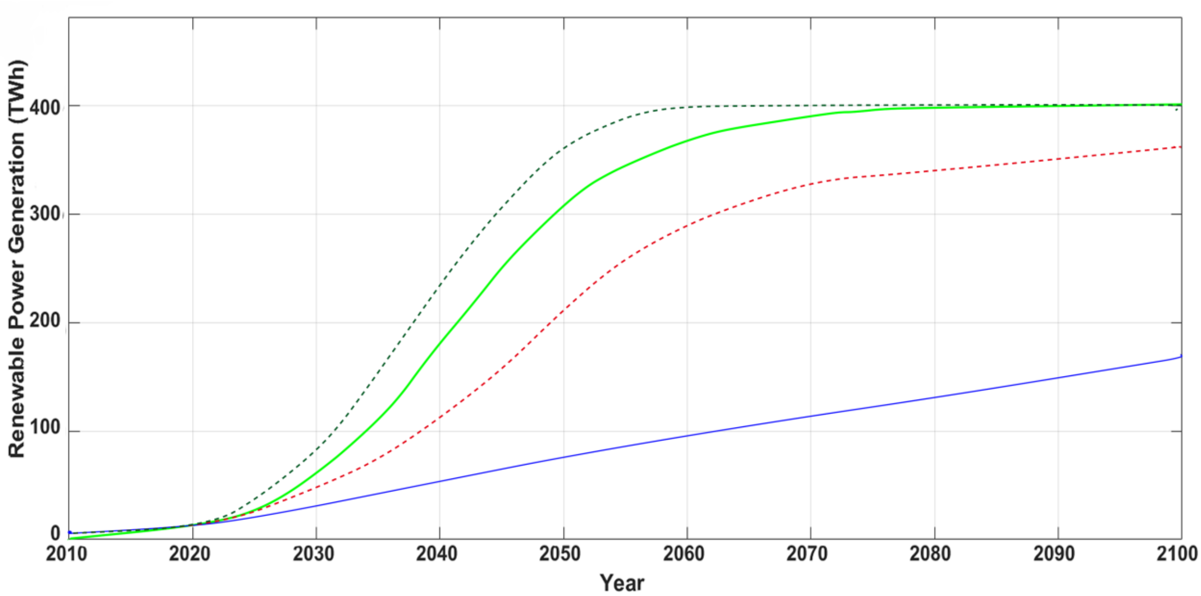


Figure 42 Impact of Income Growth Variation on RE

(Following Variables' Projections ——— and Business as Usual ———, -----15% increase, ------15% decrease in income growth)

Figure 42 depicts the effect of change in income growth rate on renewable power affordability. It is evidentially shown in a few studies that income growth supported renewable usage in many countries, including Bangladesh itself (Bradshaw, 2010; Hossain *et al.*, 2020). A 15% positive change in the GDP growth rate produces a realising capacity change in power generation by 50-60 TWh in 2040. 15% change was inserted in the model as the economic growth models of Bangladesh often use this celling as an yearly upper and lower limits while considering uncertainty and maximum capacity of the economy to grow (Hossain, 2016). The changes are inserted in the model by increasing the year-wise values by 15%. However, A 10% change would have exactly a proportionate effect linearly as the trend function used in the model is not linear. It was logistic where a portion is exponential. Therefore, a higher rate of change would incur exponentially higher transition capacity in case of income. It clearly shows, according to the model, purchasing power will have a profound impact on the transition capacity. Logically, it stands the same as income growth and has a multiplier effect on several other variables. Consistent income growth also generates trust among foreign donors, assuring the capacity to repay their invested capital in a developing country. Agencies like the IMF or World Bank often carefully consider and forecast the receivers' capacity to repay the loans or use the grants properly as expected. Bangladesh's booming financial capacity rationalised the previously provided support from the World Bank and GTZ to promote green electricity in Bangladesh through the mass deployment of solar home systems. They were convinced that with the consistent growth in socioeconomic and sociotechnical capacity enhanced by income growth, Bangladesh could realise the project. Later, the expectations came true. It is reasonable to assume that one can take a more significant risk in adopting novel technologies with higher purchasing power than one with lower financial capacity (Triyanto *et al.*, 2017). The higher-income level also motivates earners to add appliances to their daily activities, increasing the power demand (Taheruzzaman and Janik, 2016). Nevertheless, the rising demand subsequently motivates more generations persuading the traders with higher rates of return.

However, the income deceleration or high inflation trends are also to be considered as they often nudge the world economy. The model exhibited a sharper impact of such an unavoidable collapse in income on renewable aspirations. It shows the transitioning capacity would be pared down at a higher rate than the same numerically valued income increase can heighten it up. In Figure 42, in 2040, the 15% income increase trend boosts the capacity by 40 TWh. However, in the same year, a 15% less income trend would reduce the expected capacity by 60TWh. The probable reason may be the multifaceted effect of income growth on other variables.

5.1.3 Impact of the carbon tax or carbon trading

In contrast to past research, this study makes the gross domestic product an exogenous variable and compares carbon tax and trading mechanisms' environmental, energy, and economic implications. Both carbon trading and carbon tax have considerable emission reduction potential, assuming a constant GDP effect; however, the relative emission reduction efficiency of the carbon tax is greater than that of carbon trading (Jia and Lin, 2020a). This advantage grows with time. Carbon trading has a detrimental impact on the power industry and other energy-intensive industries participating in carbon trading. Several studies investigated the effect of subsidies, carbon tax policies, and carbon emission trading policies on investment in green power development to reduce carbon emissions (Dixit *et al.*, 2018; Herndon, 2018; Sun *et al.*, 2022). They conclude that it is difficult to identify a suitable carbon price, and carbon price volatility will likely lead to a backshift in investment from green power to thermal power (Sun *et al.*, 2022). High carbon costs will further reduce investment in the energy sector, which will eventually contract. Therefore, Bangladesh, a country with poor risk-taking capacity, must carefully consider this option.

Some studies suggested the following carbon policy proposals to encourage the development of renewable power among developing countries.

1) From the standpoint of stimulating renewable energy growth, a carbon emission trading strategy is more effective for a developing economy with poor energy access than a carbon tax policy (Dixit *et al.*, 2018). This study indicates the government should establish a carbon emission trading strategy without subsidies. Investors would prefer to invest in wind power under a carbon emission policy instead of a carbon tax policy. The carbon emission trading regime could maximise the proportion of green power investment and achieve the carbon reduction target without subsidies.

2) A free provision for trading carbon emission reductions should compensate for the decline in renewable energy investment induced by eliminating subsidies (Sun *et al.*, 2022). It would allow a renewable power development plan to be implemented without increasing the government subsidy deficit. Establishing suitable quotas and market prices for carbon emission rights could encourage businesses to continue investing in green power during the transition period without subsidies and prevent a decline in green power investment.

3) The future ‘’carbon emission trading’’ marketing strategies should be formulated following the suggested price and free quota(Jia and Lin, 2020b). The free allowance and carbon trading prices must be reasonably structured to serve as anchor prices for future carbon trading. The percentage of free allowances (no-carbon-taxation’s minimum limit) in the carbon emission trading regime should not exceed an optimum level. When the free quota reaches the threshold limit, eliminating subsidies will reduce the trading price for carbon emissions to a certain amount. Once subsidies are eliminated, the trade price for carbon emissions should be fixed accordingly. Therefore, the carbon emission trading market with such free quotas and carbon pricing range could encourage firms to engage in green power for developing countries.

A few studies have demonstrated that carbon taxes and broad-based charges on greenhouse gases are powerful tools for promoting cleaner fuels and decreasing energy consumption (Jia and Lin, 2020b). Carbon taxes, which are a logical extension of the system already in place to collect fuel taxes, have the potential to generate substantial revenues and are both feasible and potentially beneficial. The health and welfare of the Bangladeshi people, among other national interests, make this a priority. Despite this, carbon taxation will likely face considerable political obstacles, such as lobbying by fossil fuel stakeholders (such as public transport operators and power producers). The opposition from the public due to the tax's price repercussions, lack of transparency regarding the tax's winners and losers, and the notion that taxes lower welfare and raise unemployment are also the challenges. Therefore, carbon taxation in Bangladesh requires the impact analyses of multifaceted, interconnected influential factors.

If carbon taxes are applied optimally on the carbon-emitting systems, it can positively propel the renewable energy expansion. The optimisation of taxation may be a multimodal approach considering incentivisation in renewable use and charging in fossil-fuel combustion. Since Bangladesh is one of the minor emitters, the high-emitting countries can also purchase their carbon allowance from it to rationalise their emissions. Suppose independent power producers generate and sell electricity from green resources to the government. In that case, the taxation and financial mechanism must support the green traders through incentivisation and tax relaxation, as coal power is still more bankable at a bulk generation rate.

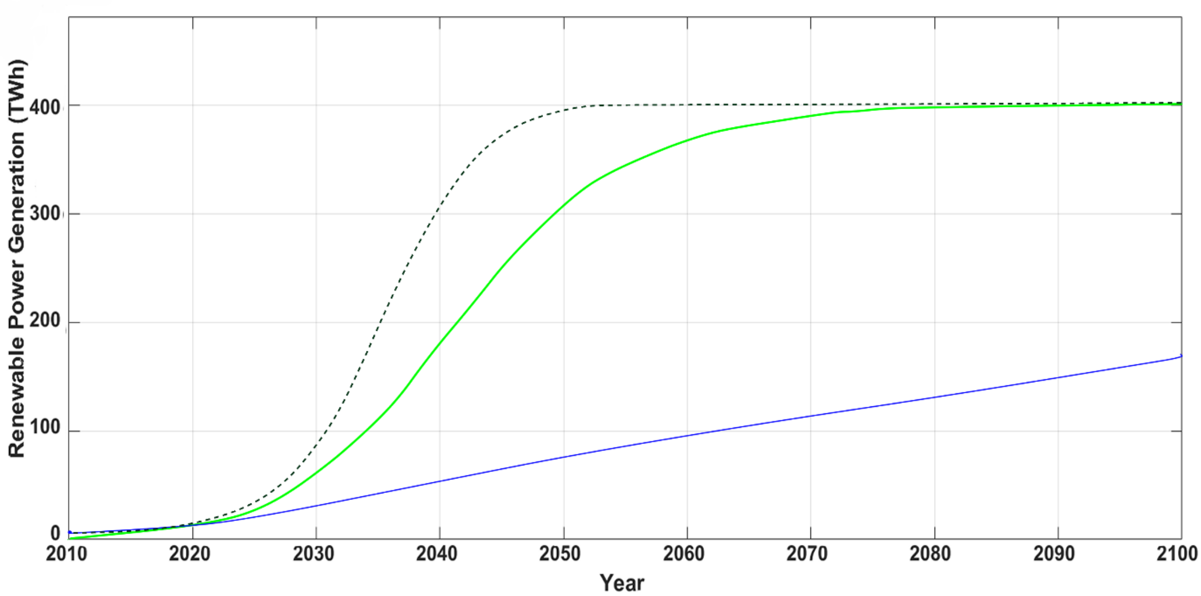


Figure 43: Impact of carbon taxation on carbon-emitting power users (----1% incremental addition in tax per annum with a 15% initial rate incurred in 2023, Following Variables' Projections —— and Business as Usual ——)

According to the interviewees in the incumbent study, external agencies may compel Bangladesh to impose carbon taxation in the future. The model exhibits a positive causation of carbon taxation on renewable expansion in Bangladesh (Figure 43). Since carbon taxation is not yet quantifiably imposed or enacted in the Bangladeshi context, the model considered that it is entrenched in the variables of foreign grants and aids and local economic affordability. However, foreign donors and buyers have warned and discouraged Bangladesh from chasing its carbon-emitting power aspirations (Sadiq Ahmed and Suvojit Chattopadhyay, 2021).

Many developed countries are now importing several items manufactured in Bangladesh. If they incentivise or tax-free goods manufactured using green energy, the manufacturers will be encouraged to go green. Foreign partners can also have a mode of compulsion approach in this regard. Therefore, locally, and cross-nationally, carbon taxation can significantly impact Bangladesh's renewable transition.

Suppose a buyer country levies a carbon tax on Bangladeshi garments by 15% if they are manufactured using energy from carbon-emitting systems. In that case, Bangladesh would propose a monetary equivalent of that 15% amounting to that power from renewable systems in that production. The cut-down amount of carbon may assess the monetisation. The factory buildings are already using the net energy metering schemes to reduce their carbon footprints and installing several rooftop solar panels. However, the progress may be accelerated at higher rates if foreign buyers can invest in the scheme. This way, the policymakers of Bangladesh have decided on a reasonable transition rate if such a carbon tax is imposed on Bangladeshi exportable products.

Bangladesh has recently graduated from the list of least developed countries to a developing state. Its electricity production also rose exponentially in the last decade compared to the previous ones. Due to lower prices and better reliability, its policymakers are still stuck on fossil-fuelled options to meet the increasing energy demand. The energy roadmaps and masterplans are heavily inclined towards carbon-emitting systems. However, Bangladesh will be compelled to import most of the fuel in the future as its local gas is running out rapidly. In addition, the fuel price exhibits intolerable spikes that Bangladesh can barely absorb with its poor resilience capacity. While the country is now becoming an attractive destination for international investors, foreign investment in the green power generation sector will be welcomed by the stakeholders and policymakers in Bangladesh.

5.1.4 Impact of the Rise of renewable power system efficiency

Many believe a solar panel's efficiency is the most significant factor when purchasing one. However, the most important factors are the manufacturing quality related to real-world performance, reliability, after-sale service, and warranty clauses (Ahmed and Helgason, 2015). The term 'efficiency' is frequently used; however, a slightly more efficient panel does not necessarily indicate a higher quality panel. In general, solar panel efficiency is a good performance indicator, particularly since many high-efficiency panels employ higher-grade N-type silicon cells with a better temperature coefficient and less power loss over time[24].

The techno-economic efficiency of the power systems is often connected to the length of the payback period. Investors are always interested in faster payback periods. In terms of the environment, a solar panel with more efficiency often returns the embodied energy (energy used to extract the raw materials and produce the solar panel) in less time. Depending on the region, most silicon-based solar panels return the embodied energy within two years based on extensive lifespan analyses (Wang *et al.*, 2019). Since the technoeconomic efficiency of solar panels has improved beyond 20%, the payback period has decreased to less than 1.5 years in many places (Raugei, Bargigli and Ulgiati, 2022). Improved efficiency also means that a solar system will generate more power during a solar panel's normal 20+ year lifetime and thus pay back the initial investment sooner, thereby enhancing the return on investment (ROI).

Solar energy is the most feasible renewable resource in Bangladesh. The efficiency of Solar panels or modules is crucial for generating power to exploit the benefits at their maximum. Solar module efficiency measures the quantity of sunlight (irradiance) that falls on the surface of a solar panel and is converted into electricity. Due to the tremendous developments in solar technology over recent years, the average panel conversion efficiency has improved from 15% to over 21%. This huge gain in efficiency resulted in the power rating of a standard-size panel jumping from 250W to nearly 400W[25].

[24] https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels
[25] https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels

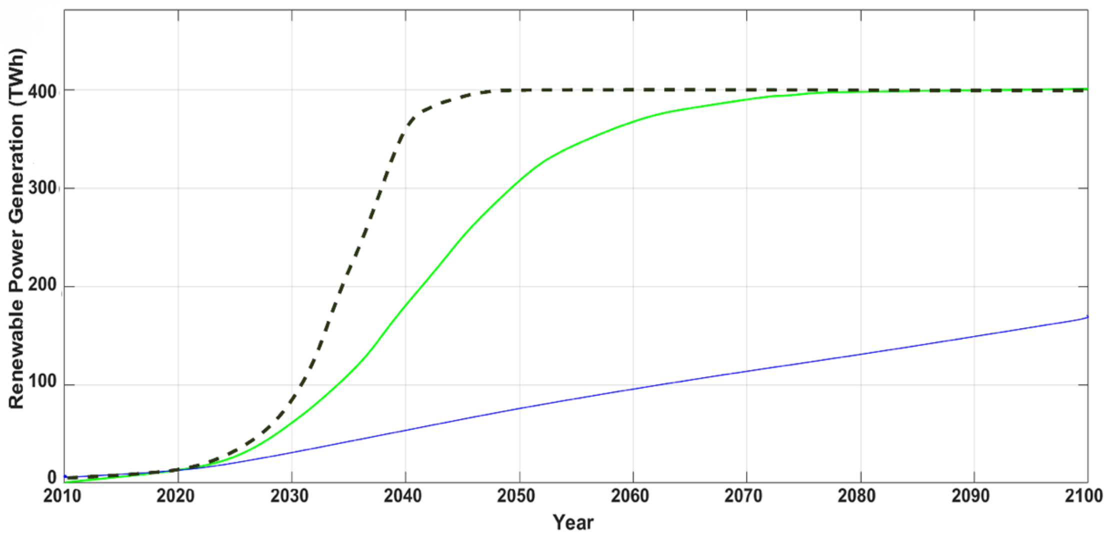


Figure 44 Impact of efficiency rise (-----1 percentage point/annum, Following Variables' Projections —— and Business as Usual ——)

Figure 44 shows the impact of the efficiency rise in the renewable system. It is a technological advancement scenario where the same land area's solar panels will produce double power if the efficiency of those panels is doubled. It is because of the linear trend in efficiency rise used as the variable trend function in the model (Table 9). However, there are very good chances for accelerated growth in the efficiency rise in near future due to exponential rise in the R&D in such domain (Weib, 2020). Some papers suggest that the efficiency rise may get doubled by next decade (Jeremy, 2021). Therefore, the simulation displayed a shifted transition by doubling the rate up to 50% (Then ceased). The renewable share will perceptibly rise with the escalation of such technology's technical efficiency (η_R). In the 21st century, efficiency continues to rise, and the future forecast shows no signs that efficiency will stop increasing (AL-Rasheedi et al., 2020).However, in the last ten years, the efficiency rise is not so progressive, but in Bangladesh, the importers are now importing good quality panels following the government rules and regulations. In addition, the cost of solar power (Bangladesh's primary green energy source) has decreased. Therefore, the rise in solar capacity and the willingness to buy solar power will continue with both rises with the increasing efficiency of solar power systems. However, the modelling was done for simplicity, considering the normal progression mode in technical advancement.

5.1.5 Impact of Foreign Grants and Aids

Historically, foreign partners primarily contributed to the renewable power expansion regarding funding and technical assistance in Bangladesh. However, the first renewable initiative was a hydroelectric power plant at Kaptai[26]. The first stage of construction, which began in 1957, was finished in 1962. The power plant's dam, spillway, penstock, and two 40 MW Kaplan turbine generators had all been constructed at this point (1 in Figure 45). A 50 MW generator was commissioned in August 1982 (2 in Figure 45). The fourth and fifth generating units, including a 50 MW Kaplan-type turbine, were added in October 1988, bringing the total generation capacity to 230 MW (3 in Figure 45). The Overseas Economic Cooperation Fund and the United States funded most of the project. Then after a long gap, the solar home system project was funded by The World Bank and German GTZ in 2010 (4 in Figure 45).

[26] https://en.banglapedia.org/index.php?title=Dam

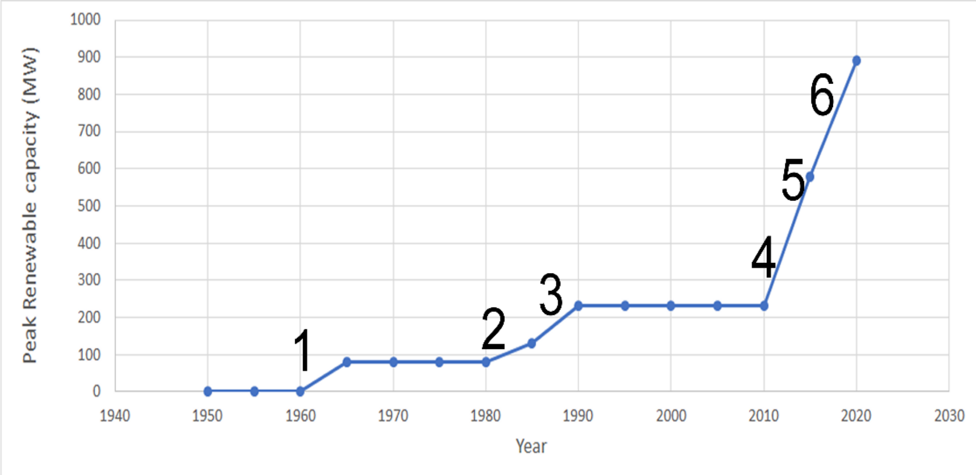


Figure 45 Contribution Chronology of foreign aid in renewable power expansion in Bangladesh

It removed the inertia giving momentum to the flow of foreign support in aiding the renewable power escalation. Since then, the injection of external aid and grants have continued to boost Bangladesh's green power generation at an accelerated pace (5, 6 in Figure 45). It is evident from this progression history that renewable propagation has always been initiated, supported, and accelerated by foreign assistance in Bangladesh, and the legacy continues.

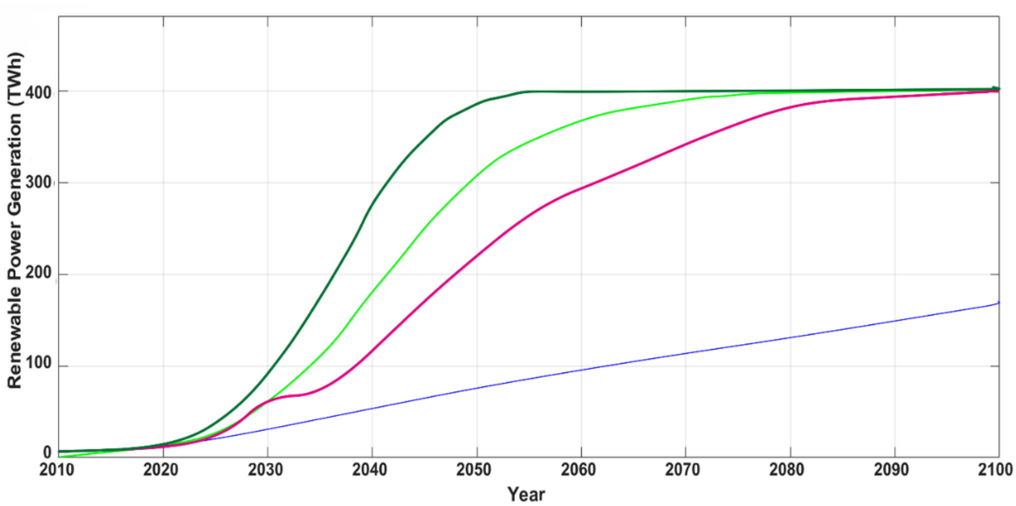


Figure 46 Impact of Foreign Grants and Aids (— Foreign grant ceased after 2030, — Foreign financial support increased by double, Following Variables' Projections —— and Business as Usual ——)

Figure 46 presents the profound impact of foreign grants and aid on the transition capacity of Bangladesh. If the Grants and Aids are doubled, the country will reach its saturation capacity to transition within the next thirty years only, where it will take twenty years more with the same trend. However, it is not pragmatic to think that foreign investment or grants will always flow in, as Bangladesh has already graduated from the least developed country status to a developing one. The graduation will decelerate the entrance rate of grants and aid in the renewable energy sector. However, the scopes for FDI (Foreign Direct Investment) inflow are likely to expand as the green power business may become bankable due to the enhancement of affordability and infrastructure development. A study by Parab et al. built and studied a sustainable development model to show the relationship between FDI inflows and the expansion of renewable energy use. They used panel data analysis to examine data from 43 specific nations between 2005 and 2017 (Parab, Naik and Reddy, 2020). Their findings demonstrated a long-term association between FDI inflows and renewable energy consumption and a robust causal unidirectional correlation. It is also a proven fact for

Bangladesh, as most of its renewable achievements hitherto have been supported and funded by foreign entities. For example, the renewable escalation in Bangladesh since 2010, has been extensively aided by the climate change fund from WB and GTZ. Nevertheless, in the future, when Bangladesh will have more affordability and graduate from LDC, the chances will be less to have those aids or grants. Therefore, policymakers and visionaries must infer that the flow of grants or aid will not remain consistent forever. It would instead transform into an investment sector by interested multinational energy dealers. The scopes may change as follow:

- ⇨ The policymakers have intentions to introduce and enact various incentivisation schemes. These schemes may make renewable power businesses attractively bankable in Bangladesh.
- ⇨ The rate of return from agribusiness is weakening, and Bangladesh's service economy is thriving. In addition, recent climate change affected many regions of Bangladesh with prolonged inundation and saline water intrusion, lessening the crop yield. These transition traits may make land use for solar power generation more feasible than crop farming in the future. Energy traders may feel more attracted to invest in Bangladesh's renewable power generation sector.
- ⇨ If the government can protect the erected renewable power plants (by declaring them Key Point Installations) funded by foreign investors and smoothen their power business, the bankability will rise, and the investment will flow in.

5.1.6 Land Availability Impacts

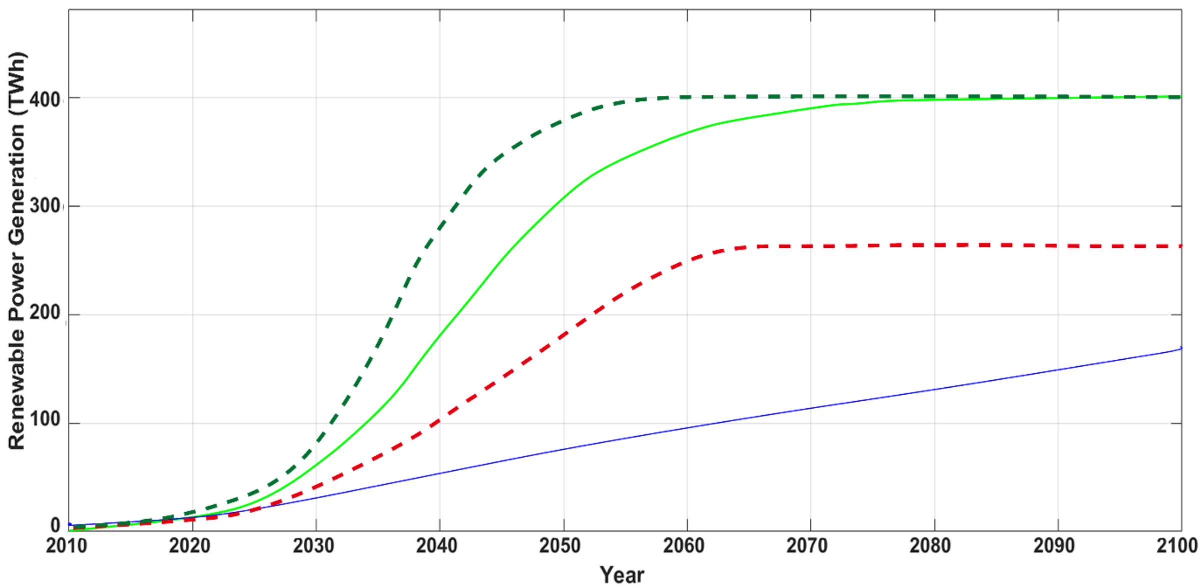


Figure 47 Impact of Land Availability on plausible transition (– – Land availability rate lessened by 50%, – –Land availability rate increased by 50%, Following Variables' Projections —— and Business as Usual ——)

Land availability seems to be another strong influencer for the green power transition in Bangladesh in the simulated model (Figure 47). The stakeholders often make excuses against green power escalation, saying sufficient land is unavailable for a viable solar power plant in Bangladesh. The per capita land is minuscule compared to the minimum civic need (Sohrab Hasan and Rafsan Ghalib, 2022). If the lands become available as agronomy shifts to the financial service economy, the solarable lands may be viable for power producers. The rate at which the lands are becoming available if that rate is increased by 50%, 100% green power may be possible for Bangladesh by 2050. Still, it is not a pragmatic prediction due to the system inertia and lock-in. The economy is still heavily dependent on agrarian activities. The lion's share in employment is still generated from agriculture. Though the shift towards the service and industrial economy is fast, land is not becoming available at the same pace. Emphasising food security for millions of people over energy is the foremost reason behind it. Green power generation may halt if the land availability rate is lessened by 50%

and becomes stagnant after 2060 (Figure 47). However, less availability will put more pressure on the rooftops, increase the growth of green power imports from neighbouring states and technoeconomic efficiency of the RE power systems.

5.1.7 The Impact of PV Electricity Price on Transition

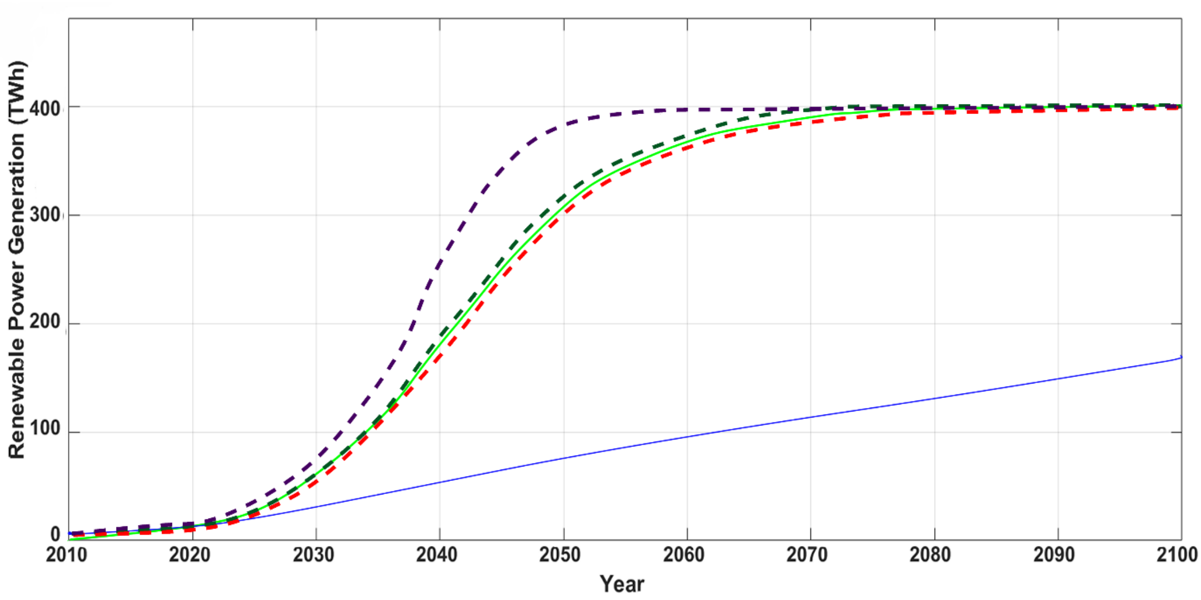


Figure 48 PV electricity (Renewable Power) price impact on the transition (— BaU, – – PV electricity price (LCoE) lessened by 5%, – – LCoE Increased by 5%, – – PV Power price rate purchased by Government lessened by 50%)

Figure 48 delivers the impact of solar power LCoE on the transition, which does not seem very influential compared to the other variables in this model of Bangladesh context. The causality may be regressive as the price did not change much in the last ten years in Bangladesh, but the escalation went up rapidly compared to that. However, if the price is widely controlled by incentivisation or taxation, the scenario may shift significantly (Figure 48). The current feed-in tariff rate is around 10 US cents for large PV plants with over 20MW, which has been the same since 2018 (PD, 2023). Nonetheless, green power generation increased by 300% during the same period. The price is still higher than the domestic tariff rate (~5 US cents). It might be the effect of subsidisation by the government to make the deal attractive for the power dealers who sell PV power (Feed-in) to the national grid. Therefore, though the power price remained constant for a while, rationally, the green power generation may be motivated by the lucrative purchasing price rate set by the government.

5.1.8 Impact of Green Power Import

Simulated outcomes suggest that importing green power from neighbouring states will directly propound the total green power (Figure 49). Logically, the imported power will be directly added to the total electricity generation capacity. With a more prominent capacity factor of hydropower from Bhutan, Nepal and India and Solar from the Indian desert (Asia, Lanka and Mahmud, 2012), Bangladesh may enhance its green power considerably through effective diplomatic efforts initiatives. Moreover, it can connect to the regional grid where the neighbours may add their extreme green points.

Large-scale solar power production in Bangladesh will necessitate a lot of expensive and rare land. Even though the country desperately needs electricity, replacing crop farms with solar or wind farms in territories producing food is impossible. However, Bangladesh can suggest that the resource be renewable rather than fossil-fuelled since it already imports electricity from its neighbours. Bangladesh can increase its renewable energy proportion without putting a strain on its limited lands. There are huge hydroelectric potentials in Bhutan and Nepal, which are more dependable than solar during monsoon seasons. Bhutan has previously accepted Bangladesh's offer to install its hydropower plants and purchase the power (Asia, Lanka and Mahmud, 2012).

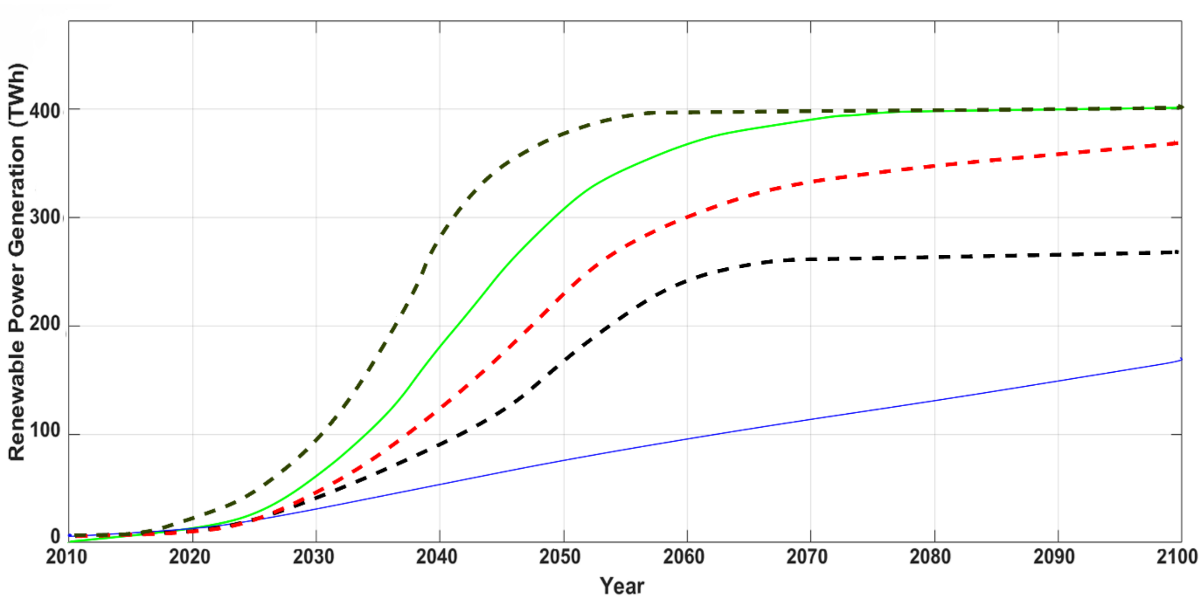


Figure 49 Impact of Green Power Import from neighbouring countries on Transition (— BaU, – – Import lessened by 50%, – – increased by 50%, ------ No import)

However, due to a few factors, expert opinions are found to be split. The diplomatic reliance between the nations has not yet been sufficiently developed to rely on large-scale electricity imports because of the irregular patterns in this subcontinent's geopolitical stability. In addition, despite Bangladesh's grid quality is growing, it cannot yet oversee power trips through extraterritorial nodes. In Bangladesh, there have already been several instances where such tripping has caused a nationwide grid breakdown. To ensure national energy security, authorities have decided not to import more than 10% of the total generation capacity from outside[27]. However, this limit needs to rise in the future as without import, it is extremely difficult for Bangladesh to go 100% green in its power sector.

The latest updates confirm that Bangladesh will receive 500MW of hydropower from Nepal by the end of 2024, and the amount may increase to 6000MW by 2030 from Nepal and Bhutan combined[28]. The hydropower potential of both countries is in surplus and surprisingly consistent. It will indeed be a giant step towards increasing the green share in the power mix, and its steady flow will pave the pathway to a green baseload supply. It may be a turning point in initialising the movement towards a regional green power network which is essential for Bangladesh to go 100% green in its power sector.

5.1.9 The Impact of Fossil-fuelled Electricity Price on Transition

Fossil fuel price is one of the primary influencers in the renewable transformation in many areas of the world (Owoeye, 2021; Gupta, 2022, Alo, 2019). In Bangladesh, 90% of its electricity is generated from fossil-fuelled

[27] https://www.tbsnews.net/bangladesh/energy/loss-making-bpdb-finds-cross-border-power-import-low-cost-option-486550

[28] https://www.tbsnews.net/bangladesh/energy/process-import-500mw-hydropower-nepal-final-stage-nasrul-649286

power plants (Zaman, 2022). However, most of them (90%) are driven by locally available natural gas. The price of natural gas is heavily regulated by the government and for power generation, it was held almost constant for decades (PeCo, 2021). Since 2009, several diesel-peaking power plants have been erected and operated across the state to fill up the peak demands. They consumed a lot of imported diesel which was also subsidised for that particular purpose. There have been a lot of disputes regarding it as billions of USD were billed as capacity charges without supplying any power to the grid. The independent power producers enjoyed indemnity through the enactment of the Emergency Electricity Generation Act, of 2009 (Alo, 2022). However, the government faced a lot of defiance from several stakeholders and was compelled to cut down the amenities for the Diesel plant owners (Alo, 2023). Upon the insertion of the yearly prices of the imported diesel into the model, it seems that the transition was profoundly influenced by the end-user diesel prices (Figure 50).

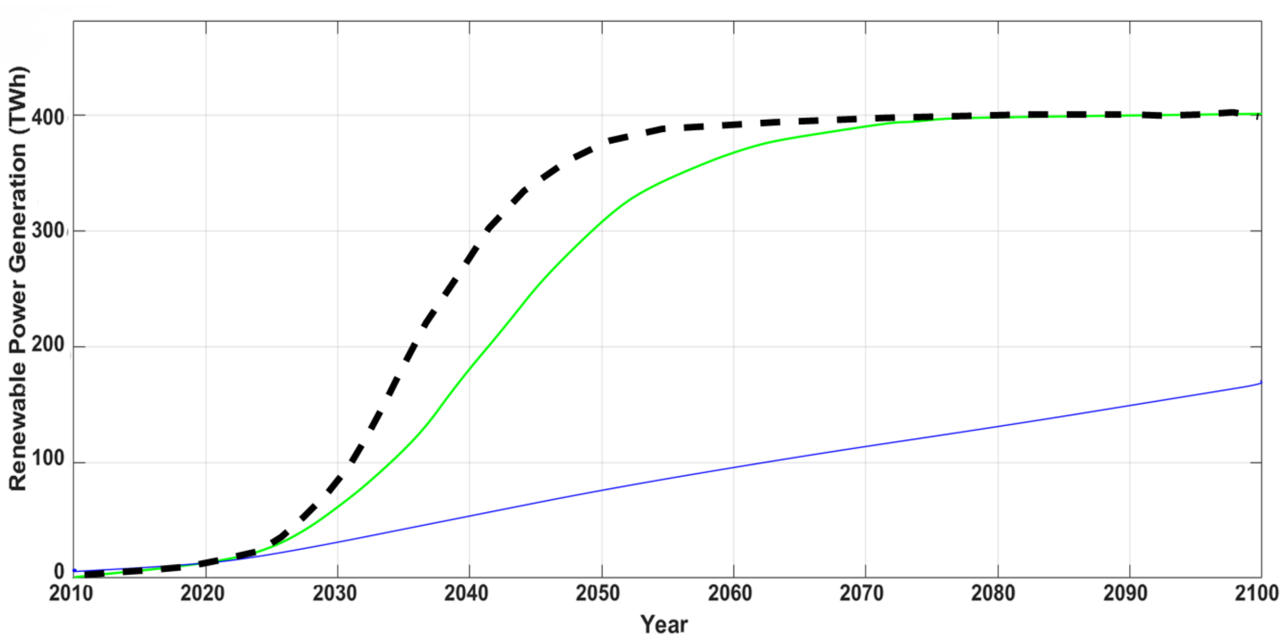


Figure 50 The dotted line expresses the rate of possible transition if the diesel fuel price increases at a double rate than the present rate

Nevertheless, the nexus is still complicated as it is subjected to subsidy and there is deep bias in the power purchase agreement in favour of the producers. Nevertheless, the government itself claimed that it is nudged by the diesel-operated power plants, and it has an honest intention to replace them (1132 MWp[29]) with solar as shortly as possible. Heavy furnace oil (HFO) is another fossil fuel used to generate power in Bangladesh. However, its price remained stable since last decade and it went considerably down thrice in that period. No new HFO power plants were erected in the considered phase as well.

EIA report forecasted crude oil and diesel fuel prices to decrease after 2022 (EIA, 2021). It may occur as EV cars are penetrating the transport market with a vast superior speed (IRENA, 2022). Therefore, the lessened demand for fossil fuels may decrease the price. It can retain the system lock-in of existing plants if compelling government policy actions are not enacted in favour of renewable propagation. However, since the power demand is rising and renewable options are getting the upper hand regarding several technoeconomic advantages over fossil-fuelled systems, the decline in the fossil fuel price may not be a strong barrier to renewable penetration across the globe. Despite such a price drop, the exponential rise in renewable adoption has already evidentially proven it (Ben-Salha *et al.*, 2022).

[29] Bangladesh Power Development Board, 2023

Meanwhile, the running diesel plants will survive another decade in Bangladesh (EnergyBangla, 2021). Hence, it may not be considered an influential factor in the renewable power expansion in Bangladesh so far. Moreover, Bangladesh has started to scrape its plans for installing fossil fuel plants already due to global climate concerns and international pressure groups. Therefore, consideration of the diesel price separately for this section seems a sensible approach for a better interpretation.

5.1.10 Impact of change in the ESS price

Energy storage prices will play a vital role in the mass transition in Bangladesh. The renewable sources in Bangladesh like solar or wind are not consistent in supply. However, electric appliances need consistent and reliable flow of current. To ensure the incessant power, energy storage is needed.

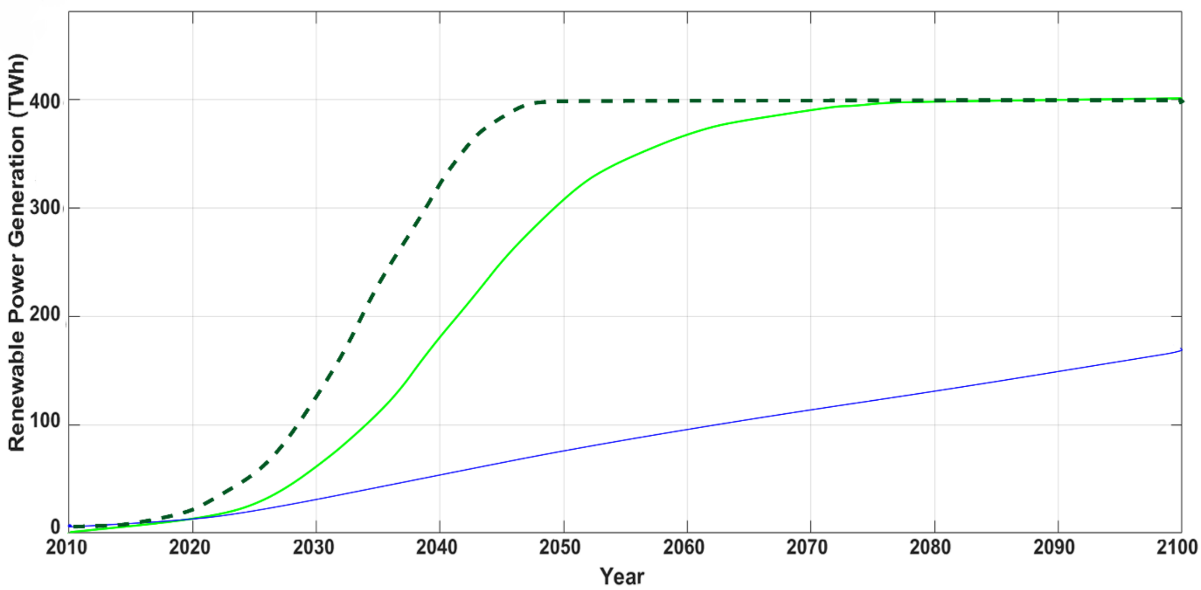


Figure 51 shows that if its price decreases at twice the current shrinking rate, the country may have a 100% transition capacity by 2040. It denotes a strong propeller for transition. Sufficient energy storage capacity will be required to move towards a green baseload supply from intermittent resources like solar or wind. Without the massive deployment of energy storage devices like batteries, a reliable inconsistent power supply from solar sources is impossible.

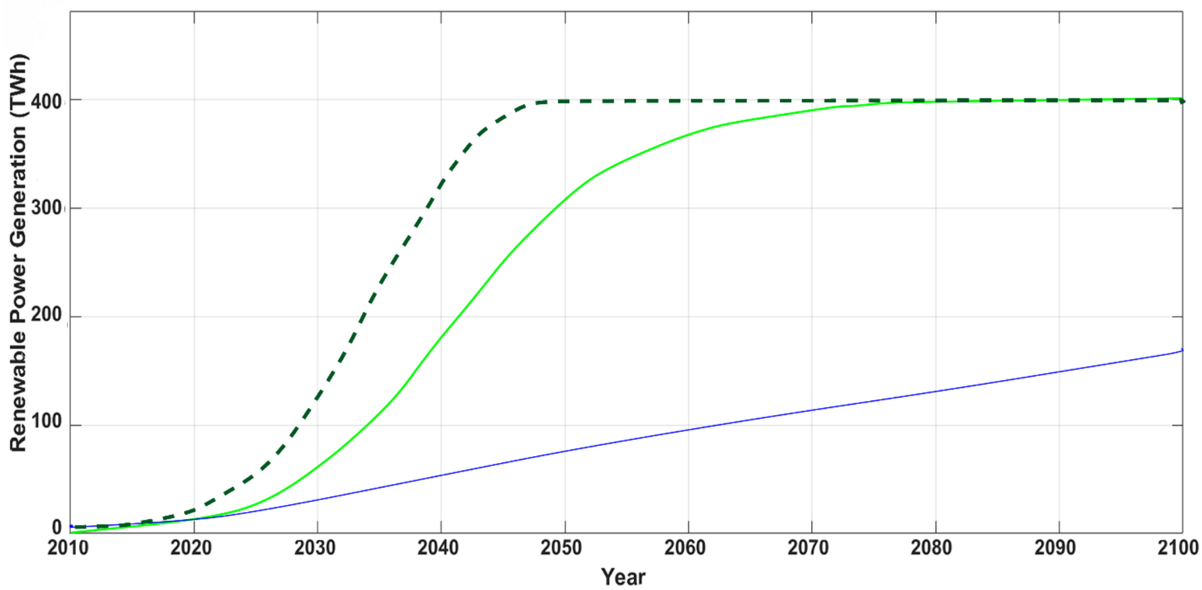


Figure 51 Impact of change in the ESS price (USD/kWh) on Transition (— BaU with all variables rising expectedly, – Linear extrapolation of the current rate, – – price drop increased by 50%)

The role of energy storage and its required size depends on grid flexibility, storage system design (selected energy-to-power ratio), VRE penetration, curtailment, and scheduling strategy (Solomon, 2019). This study referred to a series of studies on the Israeli grid. System design accuracy that conforms to the seasonal and daily variability of PV output and demand profile is essential for a system that optimally matches PV to the local electricity demand. Moreover, the studies show that the choice of storage power and energy capacity depends on grid flexibility, targeted VRE penetration and assumed curtailment. These studies show that multivariate mixes of these parameters could lead to the same amount of VRE penetration. However, the key lessons from these studies are the following:

A) Based on the seasonal and diurnal interactions of the variable renewable energy (VRE) and demand profiles of storage power and energy capacity should be adhered to. The essence of this remark stresses not only how crucial it is to choose the right two storage qualities but also how important it is to choose the right storage combination and make the best use of it. As mentioned earlier, the requirement goes far beyond the straightforward method we use to design capacity in the current system (where storage is designed for some common service). It necessitates understanding the holistic use of different storage technologies and their combined effect on delivering the necessary service. Additionally, it is crucial to employ storage resources as efficiently as possible to enhance grid penetration (Solomon, 2019).

B) Storage capacity initially creates a noticeable surge in PV penetration, but the rapid growth stops once it reaches a certain point and begins to level out. Grid flexibility determines where the levelling off (or inflexion point) occurs. Beyond these thresholds, adding storage capacity does not impact PV grid penetration. Therefore, additional techniques could assist in achieving better penetration without further enhancing storage capacity, including curtailment, demand response, and appropriate forecasting and scheduling strategies. With the combination of these solutions, it has been demonstrated that 90% of the annual need for VRE penetration may be met with less storage capacity than the average daily demand of the local grid (Solomon, 2019).

However, the simulated result of the energy storage price impact demonstrated a strong nexus to the compulsion of adopting it at a massive scale when the large-scale transition is desired. Nevertheless, before such affordability is available, the policies must be biased towards the application sectors where renewable power can be used without batteries. Therefore, net metering, direct solar irrigation, and solar charging of EVs can be ample options to exploit the scopes affordably.

5.1.11 Impact on transition if all variables are rising by 100%

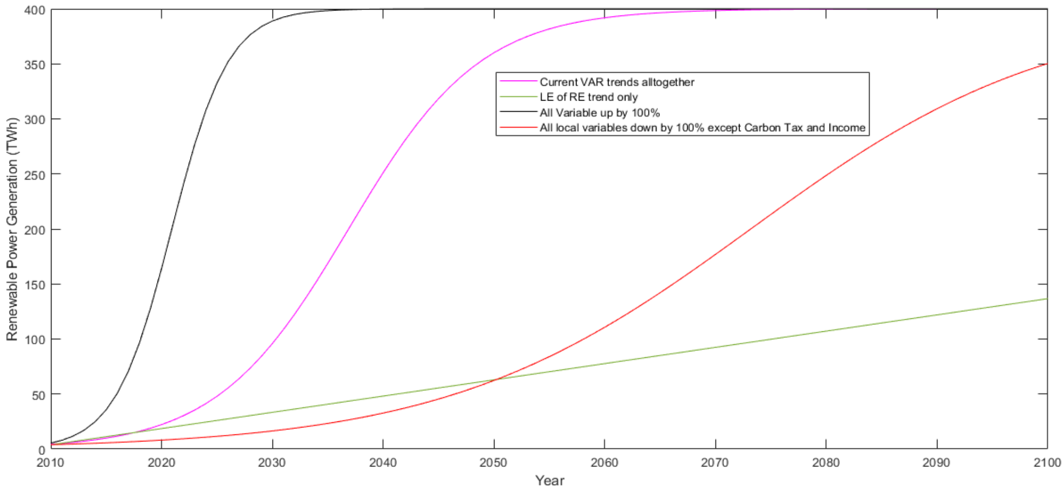


Figure 52 Generation capacity if all variables are positively rising by 100%

Figure 52 shows the dramatic change in the transitioning capacity of Bangladesh if all the variable's year-wise value is doubled, which gives the saturation by only ten years. However, it gives an understanding of the model's sensitivity to a noticeable extent and the idea of the combined effect of all the variables.

5.1.12 Impact of cyclones or other calamities

Natural Calamities or financial recessions were extremely uncertain in the past. Nevertheless, they did not remain entirely unpredictable at present anymore. The forecasts for climate change events[30] and their financial impacts[31] based on scientific and mathematical techniques have shown remarkable accuracy. Now, the recent trends robustly endorse the modelled predictions with high precision. Various past studies suggest that the frequency of natural calamities due to global warming will rise rapidly. Such changes will profoundly influence the disruption in the financial progression as well. Vulnerable countries like Bangladesh must carefully design their plans and strategies to reduce risks and enhance their recovery capacity.

[30] https://public.wmo.int/en/bulletin/weather-and-climate-forecasting-chronicle-revolution

[31] https://www.whitehouse.gov/omb/briefing-room/2023/03/14/the-importance-of-measuring-the-fiscal-and-economic-costs-of-climate-change/#:~:text=Climate%20change%20impacts%20our%20economy,most%20costly%20year%20on%20record.

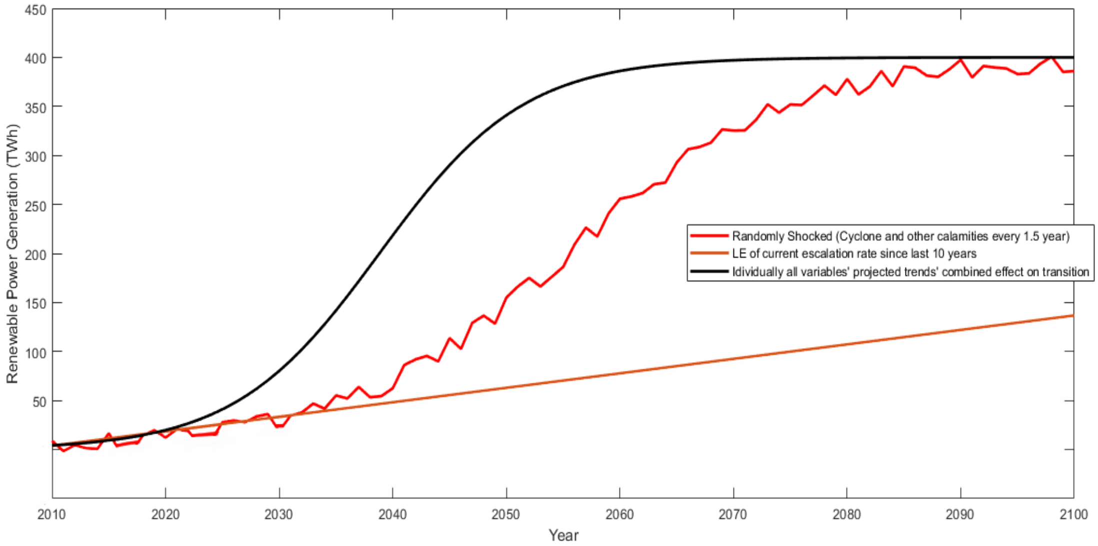


Figure 53 Shocked scenario (Impact of cyclones or floods) impeding transition growth.

Since natural calamities and uncertain disasters like pandemics hinder the development processes in every sector, green power escalation will also be affected. The country experiences a heavy marine tropical cyclone every 1.5 years. Most of the transmission and distribution lines are outdated and overground in Bangladesh. They get often torn in cyclones and tornados and the power transmission gets disrupted. An estimation suggests the massive cyclones and thunderstorms hinder the production and transmission of power by 10 TWh every year (PBD, 2020). Considering this amount with a cyclic trend in the model gives the speculation that the 100% transition may shift by 20 years if the replacement/repairing capacity and grid endurance against the calamities of Bangladesh is not enhanced (Figure 53). Therefore, it is crucial to improve such capacities for Bangladesh and replace them with underground cables, storm-resistant transmission cables etc. The coastal belt will also provide a larger land area for mass solarization due to the increasing salinity in those areas. On the contrary, that belt is the first and foremost victim of cyclones and coastal storms. Therefore, the risk of damage must be reduced by planning the projects and keeping the calamities in mind.

5.1.13 Evaluating the quality of the forecast

The predictive performance of the autoregressive model can be assessed as soon as estimation has been done if cross-validation is used (Hyndman & Koehler, 2006). This approach used some of the initially available data for parameter estimation purposes. Some (from available observations later in the data set) were held back for out-of-sample testing. Alternatively, after some time has passed after the parameter estimation was conducted, more data will have become available and predictive performance can be evaluated using the new data (Hyndman & Koehler, 2006). Cross-validation will be incorporated in the next level of this study with some updated data. In either case, two aspects of predictive performance can be evaluated: one-step-ahead and n-step-ahead performance. For one-step-ahead performance, the estimated parameters are used in the autoregressive equation along with observed values of X for all periods before the one being predicted. The output of the equation is the one-step-ahead forecast; this procedure is used to obtain forecasts for each of the out-of-sample observations. To evaluate the quality of forecasts, the forecasting procedure in the previous section is employed to obtain the predictions (Hyndman & Koehler, 2006).

Given a set of predicted values and a corresponding set of actual values for X for various periods, a standard evaluation technique uses the mean squared prediction error; other measures are also available.

The question of how to interpret the measured forecasting accuracy arises. There are two possible points of comparison. First, the forecasting accuracy of an alternative model, estimated under different modelling assumptions or different estimation techniques, can be used for comparison purposes. Second, the out-of-sample accuracy measure can be compared to the measure computed for the in-sample data points (Table 19). The forecast error (also known as a residual) is the difference between the actual value and the forecast value for the corresponding period:

E{t}=Y{t}-F{t}}\ $E_t = Y_t - F_t$ (Equation 13)

where E is the forecast error at period t, Y is the actual value at period t, and F is the forecast for period t. A suitable forecasting method will yield uncorrelated residuals.

If there are correlations between residual values, information is left in the residuals that should be used in computing forecasts. The incumbent model has subtracted some of the variables found to be correlated with others. However, there may still be some possibilities for further intervention, and future works will consider that. It can be done by computing the expected value of a residual as a function of the known past residuals and adjusting the forecast by the magnitude by which this expected value differs from zero. A suitable forecasting method will also have zero means. Suppose the residuals have a mean other than zero. In that case, the forecasts are biased and can be improved by adjusting the forecasting technique with an additive constant that equals the mean of the unadjusted residuals. The incumbent model is not an exception and can be improved by future amendments.

Another stark challenge to modelling with multiple equations is the lack of singular solutions. This model almost always generates multiple sets of solutions with different boundary conditions.

The model equation was

⇨ $R= A/(1+e^{\{k1 f(E)+ k1 f(Pfossil)+ k1 f(\eta R)+ k1 f(D) +...+...+....+...+.....\}})$ (Equation 14)

- And also, all the variable functions are a function of time or year. Hence, $E= f_1(t)$, $\eta_R = f_2(t)$, $D = f_3(t)$, $S= f_4(t)$, $G= f_5(t)$, $B= f_6(t)$, $ESS= f_7(t)$, $L= f_8(t)$, $C= f_9(t)$ etc.

⇨ $R=A/(1+Be^{\{k1\ f1(t)+k2\ f2(t)+k3\ f3(t)+k4\ f4(t)+k5\ f5(t)+k6\ f6(t)+k7\ f7(t)+k8\ f8(t)+k9f9(t)\}})$ (Equation 15)

Ten years' values for each variable were inserted in the above equation. Then, all coefficients (**k**s) are determined in MatLab by applying Vector Autoregression, solving ten simultaneous nonlinear equations like the one example below.

```
F(1) = (Rmax/(k(10)+exp(-(k(1)*0.928+k(2)*0.95-k(3)*1.9+k(4)*1.5+k(5)*0.6+k(6)*0.4+k(7)*0.1+k(8)*0.2-k(9)*1.183))))-.43;
F(2) = (Rmax/(k(10)+exp(-(k(1)*0.955+k(2)*1.0-k(3)*1.25+k(4)*2.0+k(5)*0.8+k(6)*0.5+k(7)*0.1+k(8)*0.3-k(9)*0.917))))-.6132;
F(3) = (Rmax/(k(10)+exp(-(k(1)*1.054+k(2)*1.1-k(3)*1.2+k(4)*3.0+k(5)*1.0+k(6)*0.6+k(7)*0.2+k(8)*0.4-k(9)*0.721))))-.876;
F(4) = (Rmax/(k(10)+exp(-(k(1)*1.184+k(2)*1.2-k(3)*1.1+k(4)*3.5+k(5)*1.5+k(6)*0.7+k(7)*0.3+k(8)*0.5-k(9)*0.663))))-1.22;
F(5) = (Rmax/(k(10)+exp(-(k(1)*1.316+k(2)*1.3-k(3)*1.0+k(4)*4.0+k(5)*2.0+k(6)*0.8+k(7)*0.4+k(8)*0.6-k(9)*0.588))))-1.5768;
F(6) = (Rmax/(k(10)+exp(-(k(1)*1.465+k(2)*1.4-k(3)*.97+k(4)*5.0+k(5)*2.5+k(6)*0.9+k(7)*0.7+k(8)*0.7-k(9)*0.381))))-2.04;
F(7) = (Rmax/(k(10)+exp(-(k(1)*1.610+k(2)*1.5-k(3)*.83+k(4)*7.0+k(5)*2.6+k(6)*1.0+k(7)*0.9+k(8)*0.9-k(9)*0.293))))-2.36;
F(8) = (Rmax/(k(10)+exp(-(k(1)*1.752+k(2)*1.6-k(3)*.71+k(4)*8.0+k(5)*2.8+k(6)*2.0+k(7)*1.1+k(8)*1-k(9)*0.219))))-2.62;
F(9) = (Rmax/(k(10)+exp(-(k(1)*1.909+k(2)*1.7-k(3)*.6+k(4)*1.00+k(5)*3.0+k(6)*3.0+k(7)*1.5+k(8)*2-k(9)*0.180))))-2.89;
F(10) = (Rmax/(k(10)+exp(-(k(1)*2.12+k(2)*2.0-k(3)*0.4+k(4)*3.85+k(5)*3.5+k(6)*5.0+k(7)*2.5+k(8)*2.5-k(9)*0.124))))-3.32;
```

MATLAB's solvers tried to converge F(1), F(2), F(3)………F(10) to 0 by the Levenberg-Marquardt and Trust-Region Algorithms iterating for multiple combinations of values of `k`s.

In this case of modelling for the incumbent study, the difficulty of 'no singular solution' occurred too. The solution produced by MATLAB's generic nonlinear equations solver package gives multiple value sets of coefficients k with different iterations. The modeller had to use logical reasoning in the Bangladesh context to determine the most rational set, as the multiple nonlinear regression produced different weightage for the variables. Several sets of "k" values were produced through iterations using different boundary conditions based on rational predictions to address the issue. These include the price of the energy storage system will not go negative or the amount of foreign grant will not go beyond five billion US dollars, followed by predictions from the Ministry of Finance and several pieces of literature (Prothom Alo, 2020). After achieving a comparatively rational set, simulation was carried out by varying the values of the variables. If anything, unpragmatic was produced in the forecast (e.g., Bangladesh will have the capacity to reach 100% green power by the next five years), and the set was discarded. This way, after several trials and error iterations, the best rationally conforming set of values of k was taken for fitting the model.

5.1.14 Policymakers' Announcement and model forecast

According to a recent announcement by the incumbent minister of Power, Bangladesh, by 2041, 40 per cent of the total electricity should come from renewable energy, for which the government is encouraging everyone to generate electricity from renewable energy[32]. On the contrary, the simulation shows that even though Bangladesh may have the sociotechnical capacity to shift towards 50% renewable power (of total demand) based on theoretical projections of influential factors, it is always practical to reduce the expectations on a safe margin regarding future uncertainties. An uncertain random shocked simulation with an arbitrary 10% reduction in the goal also gives the 40% attainment in the model. Therefore, 40% of total electricity by 2040 may be a real milestone both models and policymakers endorse. Here is a tabular demonstration of different scenarios caused by various influential variables with the required extent of the variances.

Table 16 Different scenarios caused by various influential variables with the required extent of the variances

Variables	**Conditions/Requirements/Projections**									
	Income per capita US$	**System Efficiency ηR (%)**	**PV power price (monocrystalline) ,LCoE of Solar (USD/MWh)**	**Cumulative Aids, Grants (mUS$)**	**Carbon Tax mUS$**	**Green Power Import**	**Renewable Budget (mUS$)**	**Land Availability (mH)**	**Price of ESS**	**Renewable Power (TWh) by 2050**
Using the progressive sociotechnical Capacity to its fullest	12000 USD by 2040	50% by 2040	25% of 2022 LCoE	Five billion USD up to 2030. Then, the financing must be continued through FDI or renewable budget enhancement	25%-30% by 2040	40% by 2050	193 billion USD by 2050	+50% of the current rate	Following the reviewed forecasts	310
Business as usual (Linear Extrapolation)	10000 USD by 2040	40% by 2040	50% of 2022 LCoE	2.73 billion USD up to 2030.	20% by 2040	15% by 2050	23 billion USD by 2050	Current rate	Current rate	70
Policymakers' Opinion	12000 USD by 2040	40% by 2040	50% of 2022 LCoE	Five billion USD up to 2030.	10%	Maximum 20% by 2050	50 billion USD by 2050	Current rate	Current rate	100

[32] https://www.pv-magazine.com/2021/06/21/bangladesh-inaugurates-largest-solar-rooftop/#:~:text=A%20Bangladeshi%20government%20minister%20has,16%20MW%20array%20in%20Chittagong.

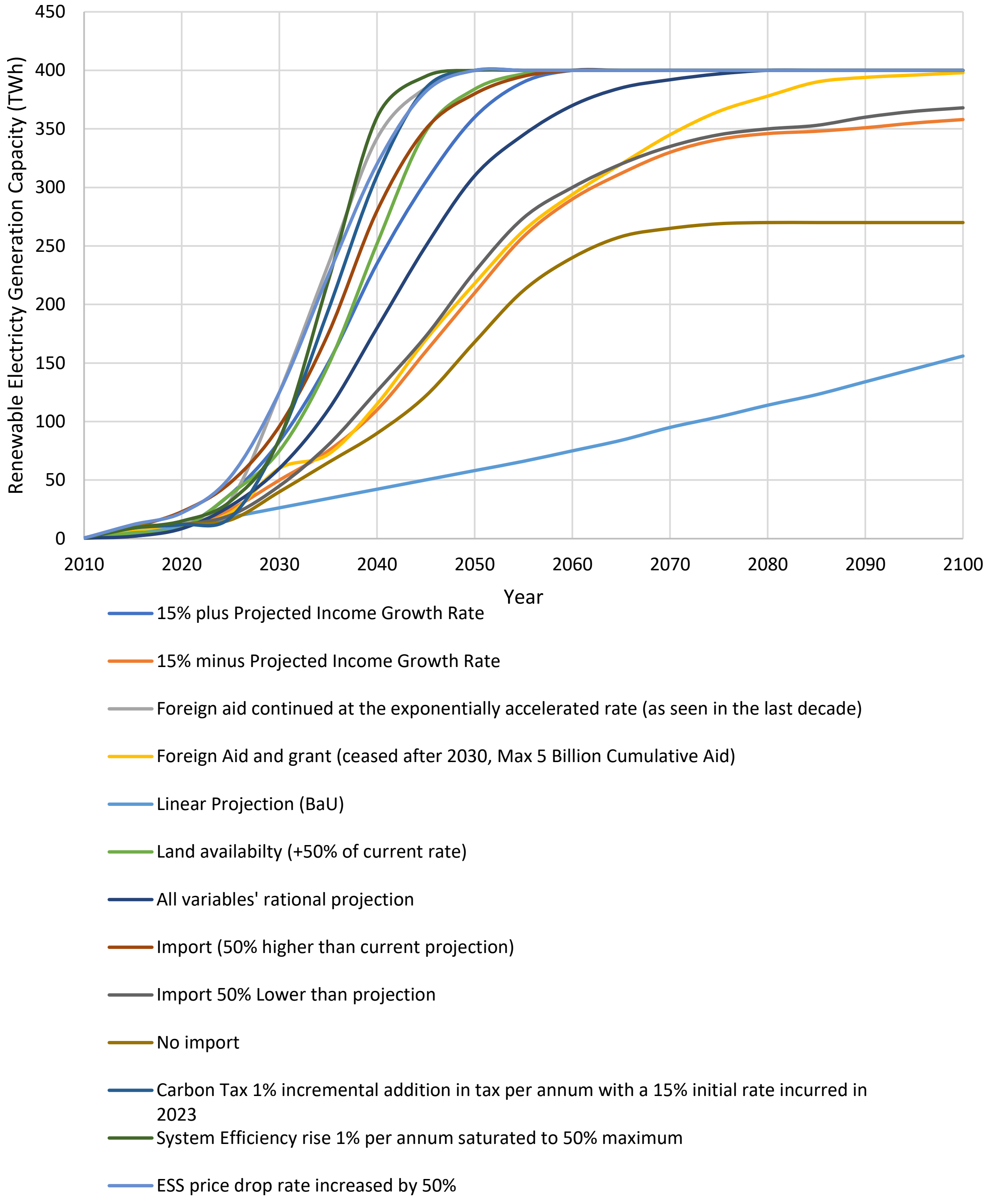


Figure 54 Simulation of impact of all variables’ changes on the transition capacity

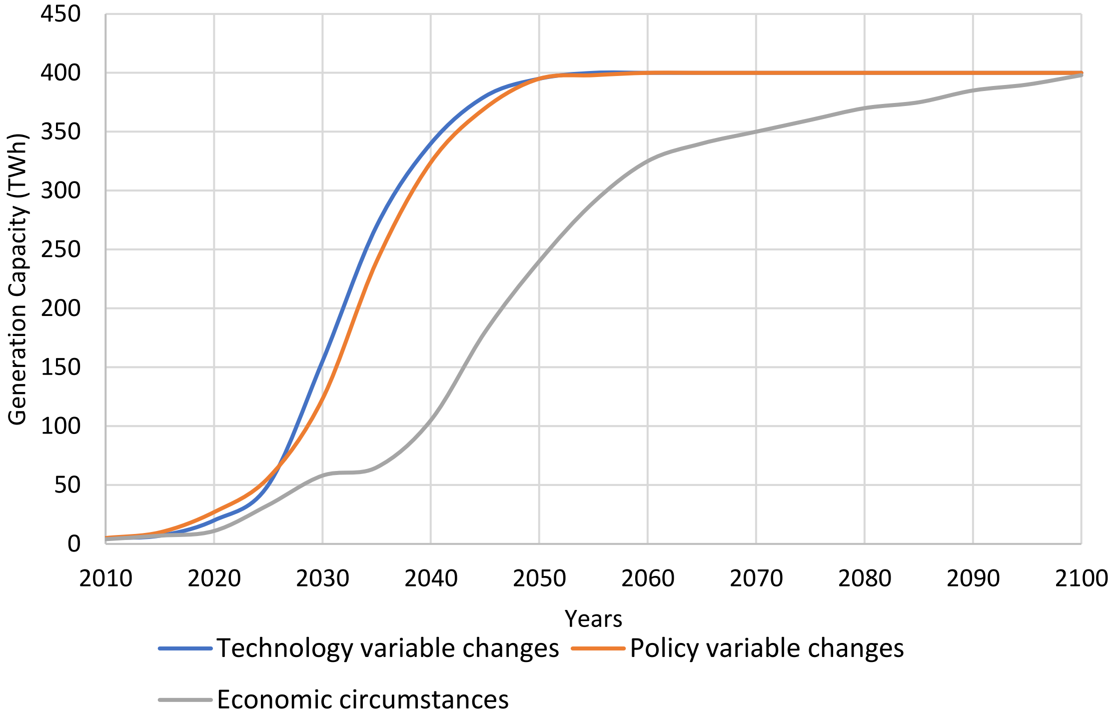


Figure 55 The combined impact on transition of different category variables

Figure 55 shows sincere policy intervention (carbon taxation, net metering, green power generation incentives, green power import etc.) can be one of Bangladesh's most powerful drivers for the renewable transition. Technological advancement (technical and economic efficiency) seems to be another prime mover of equivalent influence whereas only economic advancements without the other variables' affirmative progression the transition feasibility may not be very convincing. However, a country with a low R&D budget like ours may have to free-ride the endeavours going on across the globe and wait for progress among the research-intensive countries in such a domain.

The plots show that, by 2040, it is not possible for Bangladesh to achieve the target of 100% renewable electricity. However, with honest policy intervention coupled with adoption of updated technologies, a significant portion (75%) of power demand can be met from green resources. Challenges will occur in managing land, adopting large scale ESS and green power import from neighboring states. All these challenges may aggravate if the consistent economic progress is disrupted by uncertainties because it influences all factors. The model simulation assumed that a consistent economic growth followed by Rostow's growth pattern.

6 Interview and Survey

The rationale and methodology for conducting the survey and interview were discussed in the methodology section.

6.1.1 Survey Questionnaire

Table 17 Survey Questions

Please provide answers to the following statements:	Strongly disagree (1)	Disagree (2)	Neither Agree nor Disagree (3)	Agree (4)	Strongly Agree (5)	Remark
❖ Bangladesh is affected by climate change	☐	☐	☐	☐	☐	
❖ The country of Bangladesh is directly responsible for the climate change effects it experiences	☐	☐	☐	☐	☐	
❖ Bangladesh has sufficient renewable energy resources to support its electrical power demand	☐	☐	☐	☐	☐	
❖ Today, renewable electricity prices can be lower than fossil fuel power prices in Bangladesh	☐	☐	☐	☐	☐	
❖ Bangladesh needs to take initiatives for massive renewable adoption now	☐	☐	☐	☐	☐	
❖ Bangladesh is moving on the right track towards renewable-based power generation	☐	☐	☐	☐	☐	
❖ Rooftop solar power (photovoltaics) is a major option for mass renewable deployment in Bangladesh	☐	☐	☐	☐	☐	
❖ Bangladesh needs large-scale solar power farms	☐	☐	☐	☐	☐	
❖ Renewable energy use can protect the environment	☐	☐	☐	☐	☐	
❖ The Government is the key actor in the promotion of renewable power in Bangladesh	☐	☐	☐	☐	☐	
❖ Foreign partners/investors are required to support Bangladesh's Renewable Power Generation Sector	☐	☐	☐	☐	☐	
❖ Bangladesh should enhance its technical and manufacturing capacity regarding green power generation	☐	☐	☐	☐	☐	
❖ Bangladesh should stick to its fossil fuel-dominated power production till Renewable power becomes cheaper	☐	☐	☐	☐	☐	
❖ Bangladesh should reserve land for the installation of future solar plants right now as land is becoming scarce and more expensive	☐	☐	☐	☐	☐	
❖ Bangladesh should try to bring renewable power from its neighbouring countries	☐	☐	☐	☐	☐	
❖ Bangladesh should manufacture its own solar panels/wind turbines.	☐	☐	☐	☐	☐	
❖ Bangladesh should try to become a 100% Renewable power country by 2050	☐	☐	☐	☐	☐	
❖ The Bangladesh government should invest more in renewable power generation from now	☐	☐	☐	☐	☐	

❖ The adoption of Renewable power generation enhances energy security.	☐	☐	☐	☐	☐
❖ Bangladesh needs to consider offshore wind power to increase its overall renewable capacity	☐	☐	☐	☐	☐
❖ Public awareness is needed to promote renewable energy use in Bangladesh	☐	☐	☐	☐	☐
❖ Bangladesh should consider the use of floating solar power generation technology	☐	☐	☐	☐	☐
❖ The use of Renewable energy technology can open up significant employment opportunities in Bangladesh.	☐	☐	☐	☐	☐
❖ The priority for the adoption and use of Electric vehicles is to improve air quality in cities over to reduce carbon emissions.	☐	☐	☐	☐	☐

6.1.2 Participant Particulars

1. Which age group do you belong to?
   a) 20-30
   b) 31-40
   c) 41-50
   d) 51-60
   e) Above 60
2. What role do you play in the energy sector of Bangladesh (tick all applicable to you)?
   a) Policymaking ☐
   b) Politics ☐
   c) Implementation (Engineer and Technician) ☐
   d) Energy and Power Business ☐
   e) Management ☐
   f) Job seeker in the sector (students and graduates) ☐
   g) Research ☐
   h) None of the above ☐
3. How long have you been associated with your main role?
   a) Less than five years
   b) Five years or more

The responses are tabulated in appendices 10.1 and 10.2.

6.2 Analyses of the Responses of the Interviews and Survey

The interview results delivered many vital aspects of renewable prospects and implementation scenarios that the study tried to investigate. Though the interview was conducted among a few people, all the interviewees were incumbents in significant positions with the prime decision-making authority on renewable power generation in Bangladesh. They included vital personnel in appropriate agencies like the Ministry of Power, energy, mineral resources, Sustainable and Renewable Energy Development Authority, Ministry of Foreign Affairs, Bangladesh Power Grid Company Limited, privately owned solar energy business firms, Bangladesh Road Transport Authority etc.

The survey was conducted among relatively younger participants working in the power sector but not yet the key decision-makers. However, these people will get promoted to positions with that authority within 5-10 years. Therefore, their responses hold substantial significance in the renewable transition in Bangladesh.

6.2.1 Key Findings from Interviews and Survey

a) Most interviewees are well aware of Bangladesh's renewable energy prospects and current state. However, they strongly believe Bangladesh is not responsible for global climate change, which is rationally a fact. A similar was found in the survey responses. Therefore, the findings hold a significant extent of substantiality. Most interview participants (who hold senior decision-making positions) pointed to solar as Bangladesh's most feasible renewable resource for electricity generation. The survey respondents opined the same.

b) Nonetheless, according to influential incumbent policymakers, wind may be a feasible option in the future with the rise in the sociotechnical capacity of Bangladesh and the improvement of the techno-economic efficiency of wind technology. The juniors are not much optimistic about the wind. Feasible wind power harvest is challenging due to many technical obstacles. Poor wind consistency with cyclonic spurts makes it an unattractive choice for investors in Bangladesh.

c) To their knowledge, resource mapping for wind and solar potential was carried out with the help of foreign and local experts, and it is now substantially influencing policy decisions regarding sustainable energy planning.

d) Though the foreign supporters and agencies did the initialisation of renewable power generation, Bangladesh is now exerting efforts to enhance its capacity. The extent of sustainable energy intents and subsequent endeavours is expanding and rising steeply too.

e) According to the interviewees, the main barriers to renewable expansion are a lack of financial and technical affordability. Improper and ineffective policy frameworks and their poor implementation are other obstacles. The reliability of clean energy resources is another influential factor inducting policy decisions.

f) The drivers include foreign funds and support, carbon tax, incentivisation, and technical advancement of renewable systems.

g) The interviewees stress foreign grants primarily for renewable advancement in Bangladesh. They opined that Bangladesh is not responsible for the global warming crisis. Hence the liability falls on the giant emitters. External entities must grant more aid and consider large-scale investments in their power sector.

h) Most of the interviewees admitted that coal seems the cheapest in terms of overall LCoE in Bangladesh. This economically advantageous position of coal power is still pushing the policymakers to remain biased towards it in a developing country like Bangladesh, which is constrained by several socioeconomic, demographic and geolocational challenges.

i) Natural gas is the next viable choice as it is locally available. However, the reserve is depleting rapidly and is estimated to be unexploitable by 2030. Furthermore, the danger of intensifying carbon taxation on the exportable items manufactured in Bangladesh and other international pressure may drive Bangladesh to consider greener options.

j) Climate change impacts due to global warming are less likely to influence the energy policy of Bangladesh as it is one of the minor contributors to carbon/GHG emissions.

k) First-world countries should be the main drivers of green transformation of the power sector in developing countries. If the global community wants Bangladesh to regress the fossil-fueled power, they should directly invest in greening the power sector of Bangladesh themselves. Nevertheless, morality or ethics is not a strong driver in economics.

l) Intense land scarcity is the main barrier to the mass deployment of large solar power plants. It exerts the highest impedance against the power sector to go 100% green for Bangladesh. Bangladesh will be most likely to increase its power import from neighbouring states. However, it has put an arbitrary threshold on the maximum imported power as 10% of total capacity. Nevertheless, the policymakers hope it may have greater flexibility in improving regional collaboration and cross-national geopolitical trust.

m) Bangladesh must invest in installing renewable power plants in other countries and import power from those. Bangladesh intends the same too.

n) The respondents do not think it is possible to go 100% green in the power sector for Bangladesh by 2050.

o) Appropriate policy formulation, sufficient funding, bringing in more foreign aid and support, enhancing technical capacity, improving system efficiency, and deploying large-scale plants are the foremost actions to maximise the renewable yield.

p) Grid capacity enhancement is essential to handle renewable systems' fluctuating generation and supply. Modern digital technology, like the smart grid mechanism, must be adopted and implemented in Bangladesh to upscale its smooth renewable transmission.

q) Bangladesh is lagging far behind in innovation in renewable power than other technologically advanced nations. However, it exhibits some optimistic intentions by recently instituting research organisations like SREDA and EPRC.

r) Bangladesh is showing increasing interest in adopting electric vehicles. It has already formulated and enacted a few guidelines in that nexus. However, it needs to improve its infrastructure to accommodate such novel technology at a larger scale.

s) According to the respondents, extensive renewable deployment may pose severe threats of a power outage, economic setbacks, and undesired environmental concerns like battery or solar module disposal if no appropriate management strategy is premeditated and enacted.

7 Closing the gaps: Policy Recommendations

If Bangladesh sincerely intends to move towards a predominately greened power sector, it must adopt several reforms and timebound action plans. The sociotechnical capacity model gives several notions and hints about the much renewable power the country affords at a particular time. Now, policymakers should formulate roadmaps and guidelines considering the challenge and scopes. Derisking the domains of reforms must be a significant concern at every step, as the economy is still in an emerging phase with many vulnerabilities. Therefore, such an enormous transition roadmap for a fundamentally essential sphere must be designed and implemented in a highly safeguarded manner so that no experimental venture incurs an irrevocable loss to its growth and public money. This section will discuss optimising the available options when a challenge in the transition pathway appears. Few of the policy directions directly extracted from the study are mentioned in the next sections.

7.1.1 Using renewable resources for charging electric vehicles

The Electric Vehicle (EV) is one of the most innovative technologies in the contemporary transportation industry. More than 22 million EVs are already on the road, and the global stock of EVs is around 35 million, with a growth rate of up to 60% relative to 2018. (Global EV Outlook 2020, 2020). It has already formed a niche market in Bangladesh. Most available electric cars are modified or imported three-wheelers and a few two-wheelers powered by lead-acid batteries. These vehicles have replaced fossil-fuelled or human-driven three-wheelers in rural and small-town regions. The lower running expenses of these vehicles compared to conventional fuel-run two- and three-wheelers (diesel, octane, natural gas, etc.) have contributed to their rising popularity over the last several years. It also generates new employment options for many rural residents and cuts the cost of delivering local items. So, from a social and economic standpoint, the relevance of current automobiles is enormous. EVs have a significant influence on the environment. According to reports, around 24% of worldwide CO_2 emissions are attributed to internal combustion engines powered by fossil fuels (Shiying and Mengpin, 2019). Air pollution is one of the most common issues in Bangladesh; thus, the situation is comparable[33]. By lowering CO_2 and NO_2 emissions, replacing internal combustion engine cars with electric vehicles might enhance air quality. The scheme would become the most sustainable if these vehicles could be charged with renewable electricity.

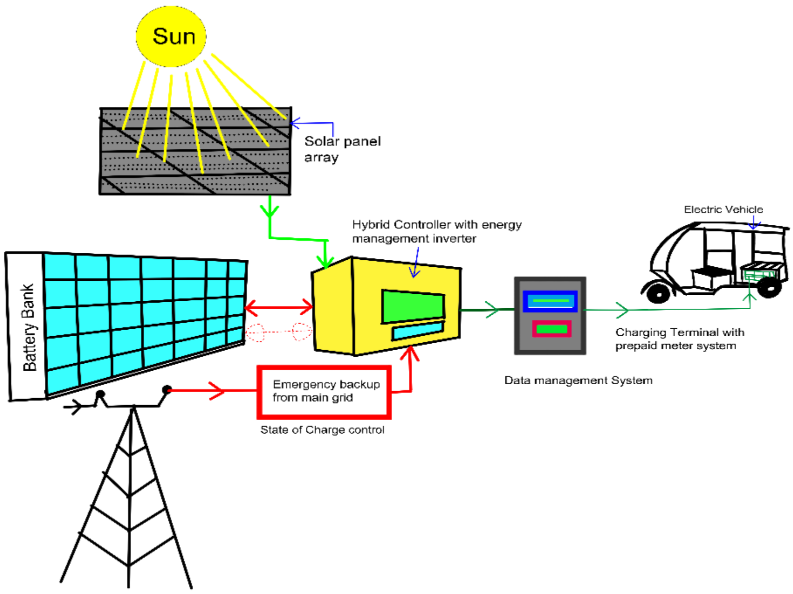


Figure 56 A schematic diagram of a solar charging station designed by IDCOL Bangladesh (IDCOL, 2018)

Recently, Bangladesh started manufacturing electric cars in the shapes of two-wheelers, three-wheelers, sedans, hatchbacks, and SUVs (Chakma, 2019). However, the entrepreneurs are sceptical about its viability since it would need extensive infrastructure development, including charging stations and sufficient energy supply (Rezaul Awal et al., 2019). According to corporate forecasts, the required amount will reach one billion USD during the next five years, beginning with local investments (Suman, Chyon and Ahmmed, 2020). Nevertheless, due to quality, dependability, and safety concerns, the Bangladeshi government has yet to legalize the existing EVs. In addition, no legislation is in place to regulate or monitor the existing high electrical usage of automobiles. In addition to energy supply concerns, disturbances in the power quality in the form of harmonics are a concern (Arefeen et al., 2019). Charging EVs regularly on a big scale would also need a revision of the current rate scheme. Simultaneously, the government must monitor the power-producing capacity, schedule the generation, and analyse the fuel cost and upkeep.

[33] https://www.thedailystar.net/environment/pollution/air-pollution/news/dhaka-again-ranks-worlds-most-polluted-city-2976026

A few pilot projects have already come up with significant prospects regarding charging these vehicles with solar power. Bangladesh has roughly one million battery-powered simple three-wheelers (similar to the Tuk-tuk of Thailand). At present, batteries are charged by the utility grid. Approximately 9000MWh (9,000,000 kWh) of power is drawn daily from the supply system to meet the demand for convenient charging (SREDA, 2021). This informal approach has increased energy shortages and load-shedding in Bangladesh. With the aid of the World Bank and IDCOL (Infrastructural Development Company Limited, a PPP of Bangladesh), the Solar e-technologies has begun a demonstration project in Chuadanga and done extensive R&D on a solar-powered battery charging station as an alternate method for charging the batteries of simple three-wheelers (Solar-E-Technology, Catherine Conaghan, Maeve Duffy, 2016).

In nexus with the extension of renewable use, the "Solar-Powered Battery Charging Station" was revealed as a potential alternative and environmentally sustainable method for addressing ongoing energy issues and supporting battery-powered automobiles (Figure 56). This charger is 22% more energy efficient than the standard, easy-to-use three-wheeler charger, significantly reducing energy demand. The cutting-edge technology utilised by Solar e-Technology includes an intelligent negative pulse current charger, a smart card billing system, and a remote data management system. With this negative pulse current charging technology, the lifespan of the simple three-wheeler is expected to be doubled.

As a pilot scheme, the project has addressed the power shortfall and fostered optimism among the general population over the past few years. Numerous people, mainly the marginalised and other low-income groups, benefit from the commercially installed solar charging systems that aim to alleviate the gradually increasing demand for electricity. Through the solar charging system, auto-rickshaws in the Damkura area of Paba Upazila are charged cost-effectively, fostering optimism among auto-rickshaw drivers and owners (Solar-E-Technology, Catherine Conaghan, Maeve Duffy, 2016). In addition to charging auto-rickshaws, the solar system has powered an auto-rice mill in the Chabbishnagar area of Godagari Upazila, which has also positively influenced the local population(Solar-E-Technology, Catherine Conaghan, Maeve Duffy, 2016).

Figure 57 This modular off-grid solar EV charger can be installed in four hours.[34]

The expected payback duration for a 400 kWp commercial project based on a 50% grant, a 35% soft loan, and a 15% sponsor equity is 4.4 years. Considering these attractive benefits, the Government must implement rules for solar-powered battery charging stations on a commercial scale. The Bangladeshi government has planned to maintain its growth trajectory and become a developed country by 2041. Vision 2021 (Taheruzzaman and Janik, 2016) as an initial objective to become a middle-income nation, Sustainable Development Goals (SDG) targets to reduce poverty and becoming an upper-middle-income country by 2030 are the three intermediate stages necessary to reach the target of 2041.

Nevertheless, the current energy strategy does not consider EVs' likely future power usage on a grander scale. Despite this, Bangladesh's power output is anticipated to increase significantly in the following years,

[34] https://electrek.co/2022/09/13/modular-solar-ev-charger/

reaching around 40,000 MW by 2030 and 80,000 MW by 2041 (Tareq and Eusha, 2020). Therefore, authorities must develop a strategy for accommodating the future arrival of electric vehicles in the local market. Hence, comprehensive research is required to determine how Bangladesh can enable EVs access to its market in the following years and what suggestions can be made to address the obstacles it will face throughout this transition. In addition, a comprehensive framework addressing transport dependability, safety, contextuality and infrastructure development is required.

7.1.2 The Potential of Solar Power from the Rooftop of Industrial Buildings

The thesis included a discrete study measuring the Potential of Solar Power from Industrial Buildings' rooftops in Bangladesh. It was published as a peer-reviewed journal paper (Talut, Bahaj and James, 2022). It showed that Bangladesh is a prominent producer of commodities worldwide. It has many large manufacturing facilities with significant roof areas that might be used to implement large-scale solar power generation systems. The study identifies and evaluates 6045 such plants with roof areas ranging from 100 m^2 to 50,000 m^2 and models the deployment of solar photovoltaic (PV) technology that can generate electricity through site-available grid infrastructure. Using net metering regulations, this deployment strengthens the case for such electricity generation. According to the study, approximately 7.4 GWp of PV capacity and 11 TWh of electricity can be generated annually on such rooftops. It represents almost 6% of Bangladesh's current electricity usage and more than 50% of the 2030 green power goal. A techno-economic analysis addressed how such utilisation might contribute to Bangladesh's 10% renewable energy goal without negatively impacting limited land. In addition, the implementation will save 13,000 acres of farmland and reduce investment costs by utilising site-available grid infrastructure to generate electricity. These findings are expected to influence policy in support of the proposed approach, not only in terms of boosting the share of renewable energy in the country's electrical supply mix but also in terms of preserving much-needed agricultural land.

7.1.3 Policy Amendment: A case of coupling up residential buildings together for augmented solar PV output

The government of Bangladesh adopted and enacted policies to ensure the mandatory installation of solar photovoltaic (PV)systems in high-rise buildings in major cities, including the capital city, Dhaka, around two decades back. The purpose was to shave off some of the demand from such buildings and sustainably meet the escalating power costs. However, many technical and infrastructural challenges were encountered, resulting in the ultimate failure of the proposal (Yamin Sajid, 2020). One identified issue was the small power availability from a single-tall building area footprint. Hence, this study examines the prospects of a modified approach for deploying PV systems on tall rooftop buildings and interconnecting their systems (arrays) to provide augmented power at scale. Here, a brief study used the theoretical estimation method to understand the feasibility of such array interconnectivity from a sample of fifty-eight buildings (Google Maps was used to measure the rooftop area of those buildings) located by a road in Dhaka city.

National Building Codes of Bangladesh for Urban Buildings enunciated that Solar Rooftop is a prerequisite for getting a national grid connection. According to that, at least 25% of the rooftop area must be covered with ``grade 1`` solar panels with other accessories like inverters, cables, and net meters. However, the outcome could not reach the objective to its minimum expected extent, let alone deliver any promising future.

The thesis undertook an exploratory analysis to assess the prospects of interconnecting the solar modules installed on densely erected buildings in the urban regions of Bangladesh. It took a cluster of houses (a model town) in the capital city where 18 similar houses were arrayed adjacently (Figure 58, Figure 59).

Figure 58 Aerial view of the model town comprising 18 buildings

Figure 59 Closer View of the Town

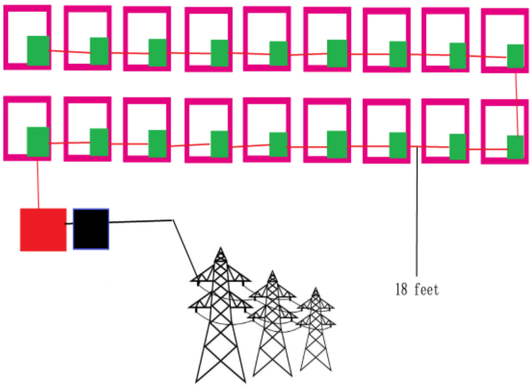


Figure 60 Interconnecting the solar panels installed on the rooftops of 18 buildings and feeding into the primary grid

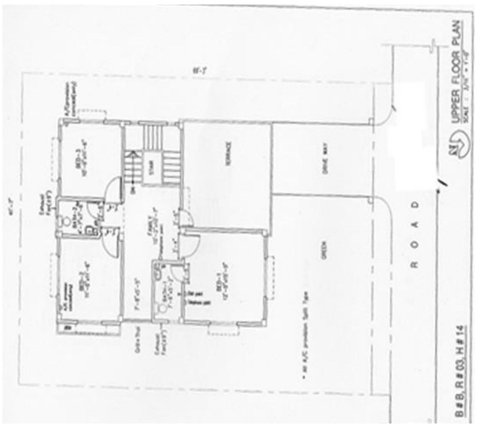


Figure 61 Floor plan of each building (GIU, 2022)

The analysis shows that such modification has several advantages over the previous approach endorsing a sustainable way to retain the policy. Such connectivity lends itself to a reduced balance of system components such as inverter and control equipment. It reduced the cost and transmission losses, enhancing its bankability. The interconnected rooftop solar can be used as an independent power producer (IPP) under the power purchasing agreement between the government and the community, and the power can be sold at a higher rate (commercial, 7.5-10UScents/kWh) than the domestic (4.5 UScents/kWh) usage. It can enhance the financial benefits and shorten the payback period considerably. Some studies and data also endorse that multiple microinverters, in aggregation, incur more conversion losses than a single larger inverter does[35]. The larger inverter allows the generator to connect more load to the system[36].

The general calculation demonstrated the following results:

- Each building (the selected model town, Pink City) has around a rooftop area of 10 m^2 and may provide a portion of 2 m^2 for installing solar panels
- space and about USD750 (as of the exchange rate of 13 August 2022) are required to realise 1.0 KWp installed solar capacity (For Dhaka, Bangladesh)
- From the 2 m^2 rooftop area on each building, solar panel installation with 2kWp capacity is possible

[35] https://www.greentechrenewables.com/question/does-larger-size-inverter-draw-more-energy-battery-bank-smaller-size-inverter-even-if
[36] https://www.energy.gov/eere/solar/solar-integration-inverters-and-grid-services-basics

- On 18 buildings, 18X2=36 kWp capacity
- Distance between two arrays   5.5m maximum
- Cable + inversion loss of up to 5% ((Zahid *et al.*, 2020))
- The average annual solar electricity from the selected location is 1468 kWh/kWp
- Net fed in electricity to the grid: 50MWh per annum

Table 18 The comparative analyses between interconnected and individual approaches

Feature	Individual	Coupled	Remark
Inverter Price	750US$X18=13500 US$	4000 US$ (Solis-36kWp-HV-5G Grid Tied Three Phase Solar Inverter)	Solis-36kWp-HV-5G Grid Tied Three Phase Solar Inverter
Real Power	Poor	Higher	More Realistic feed-in outcomes
Community usage	0	Impactful	Remarkably effectively cut down community electric bills (Street Lamp charge, Common Water supply etc.)
Losses	Higher (Considering individual inverter and wire losses)	Lower as conversion loss is also less in the larger inverter (Figure 62)	Losses are significantly lower in the case of coupled rooftop solar web.
Payback period	6.7 years (Uncertain) (Kholilullah, 2017)	4.5 years (Purchasing tariff rate high for higher solar generation. 4.5 UScents/kWh for domestic, 7.5 UScents for commercial feed-in power sale (PGCB, 2022))	The payback period is substantially attractive to the investors as it is shorter and more specific same time than the individual rooftop policy approach. The
Feasibility	Less	Higher	The interconnected rooftop grid would guarantee more rate of return, denoting higher feasibility.

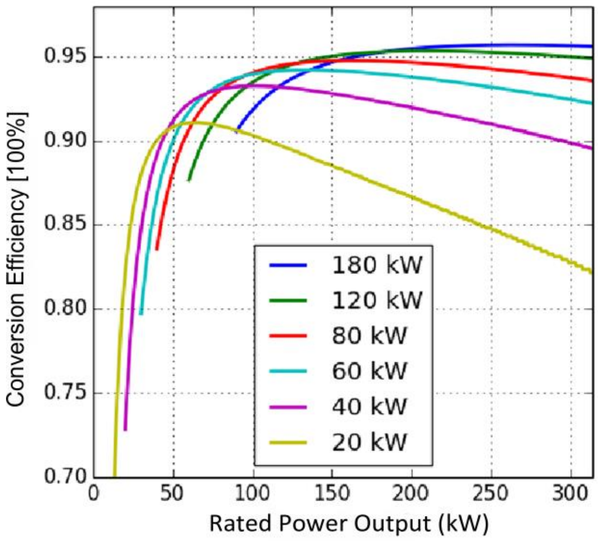


Figure 62 Conversion efficiency in the inverters of different power ratings (Malamaki and Demoulias, 2013)

If the idea can be upscaled across Bangladesh, targeting the densely housed areas, it can generate substantial green power without stressing the expensive land. The aggregated power can significantly assist in meeting the demand for pumping water or lighting streetlamps at the community level.

Figure 63 Interconnected Solar and main grid connection in a cluster village (Left, yellow boxed) in Bangladesh (Right, Box in the array=cluster houses, Grey= Rooftop solar, Green=Solar, Red= Main grid cable, the total solar cable length is much less than the red grid cables incurring less loss)

Clusters with more houses will yield more at less payback period. A similar method can be applied to the recently inaugurated mass housing projects targeting many sustainable development goals for homeless people (Figure 63). Consideration of energy storage for more extensive community applications (Mitigating load shedding, powering community halls) may be undertaken when energy storage becomes affordable.

7.1.4 Multifaceted use of Rooftop solar: An example on a dairy farm

With the socio-economic development since independence, the purchasing power of the country's people has increased. The demand for non-vegetables is increasing with different diets, and higher quality non-vegetables provide milk and meat. Due to the cessation of importing cattle from India, the demand for domestic cattle has increased, resulting in many newly established farms in the country. Farmers now see financial success. However, scarcity of fodder and inflation in electricity and fuel prices are reducing the profit margins. By using solar energy to grow grass (cattle fodder) on the land around the farm, it is possible to overcome both problems and increase the profit margin. How?

Growing livestock has high potable water requirements. The cattle consume much water to keep themselves hydrated and gain weight. A lot of water is also needed to keep the farms clean. Often this water must be raised using a water pump, which uses a lot of electricity. During extreme heat, an electric fan must be turned on the cattle's head to keep it cool; otherwise, it may die of heat stroke. This electricity is metered at industrial rates in large farms, and the bill is high.

Rooftop solar power can be a helpful tool to increase the viability of dairy in the following ways:

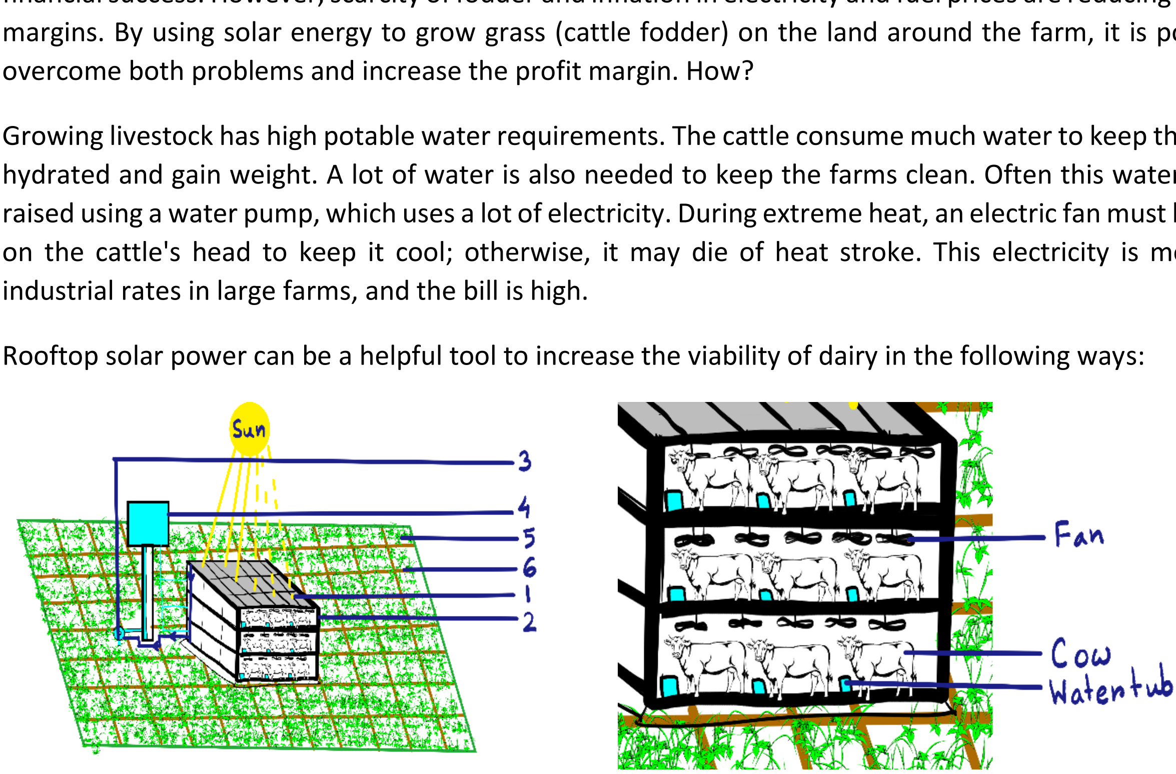


Figure 64 Multifaceted use of rooftop solar on a dairy farm (1. Rooftop Solar Modules 2. Cattle shade 3. Solar DC Pump 4. Overhead Tank 5. Grass field 6. Wastewater (Dung-mixed) Channel through the grassland)

• First, solar panels should be installed across the farm roof (1 in the figure above). Most electricity will be generated during the day, especially at noon. This electricity must be used just momentarily as it is generated. Using batteries for storage should be avoided as much as possible as their cost is high. Solar power can be used directly to drive DC fans and water pumps. When the sunlight hits the panel the most, the amount of electricity produced will also be the maximum. Profit maximisation can be achieved through the multidimensional application of this theory. In this case, the following steps can be followed:

• Solar-powered DC pumps should be installed near the farm. This pump can be submersible (underground) and installed below the ground (3 in Figure 64). When it receives a minimum amount of electricity from the solar panel (threshold), it raises water. The higher the wattage, the more water the pump can lift. When power generation stops, the pump stops working at night or in low light. In this case, time management is essential. If no separate tank is installed, the maximum utilisation of the water withdrawn at noon should be ensured. Again, overhead tanks can be installed to store water when needed (4 in Figure 64). The stored water can be used as drinking water for the cattle. The water can be channelled toward the tubs in front of each cattle. For example, the farm should be cleaned in the afternoon using water jets from the pump. A cleaner farm increases the likelihood of healthy cattle.

• Wastewater from a dairy farm is highly fertile due to the dung mixture. If it is sprinkled on the surrounding land in a semi-liquid state, abundant grass production is possible. In this case, it is necessary to construct channels to transport this waste mixed water from farm drains to land (6 in the figure above). The advantage of doing this is that the dung and the water will go directly to the land, spread evenly and greatly aid in producing grassy fodder. However, the condition, in this case, is that the land surrounding the farm should be designated for cattle fodder production (5 in the figure above). Cultivation of jumbo or Napier grass can be more profitable than rice cultivation. Solar power will directly aid in the cost-effective fertilizers and irrigation water supply.

• If the groundwater level drops in winter, water from nearby waterbodies or reservoirs can be used. Farmers will significantly benefit from setting up their farms near the reservoir. Because the electricity is used to draw underground water, it takes much less to transport surface water. In this case, obtaining more water with the electricity generated from the same number of solar panels is possible.

• Solar power can be remarkably profitable using DC fans on cattle heads inside the shade. In the scorching summer sun, when the heat peaks and the animal's chance of heat stroke are highest, this fan will spin the loudest and keep the animal calm and comfortable, preventing life-threatening heat stroke. Solar power production will decrease at night or during rain, but the heat and fan air requirements will decrease. In this way, DC fans in the farm can directly use solar power instead of recharging the batteries to increase profitability.

Not only are the prices of fossil fuels fluctuating wildly around the world, but using these carbon-emitting fuels makes the atmosphere dangerously warm. A developing agrarian country like Bangladesh cannot enter an industrial economy overnight. Moreover, if self-reliance and self-sufficiency in agriculture decrease, the food security of many people may also be threatened. Nonetheless, the shift from vegetable agriculture to animal husbandry (for sufficient protein production, as Bangladesh is still one of the lowest protein consumers) is encouraging. Because the amount of profit is not only high, but it is also essential to meet the protein deficiency of the country's malnourished people. Multipurpose use of locally generated solar power in livestock farms will play a significant role in meeting the Sustainable Development Goals related to renewable energy. Fuel and food security will be ensured simultaneously.

Another innovative idea uses RE like solar PV to run refrigeration systems like solar thermal absorption chillers, ice storage, solar water heaters and biomass gasifiers, or biogas to replace diesel generators (30–35%) and grid electricity to power milk cooling compressors during the power consumption[37]. Mini-grids can also be erected for nearby public facilities like schools, clinics, and houses, and water pumping stations for irrigation, along with energy efficiency improvements. The holistic solution will enhance the number and productivity of milk collection centres in Bangladesh, improving the quality and availability of fresh domestic milk. Estimations show, that by transitioning from diesel generators to solar photovoltaic (PV) systems and other renewable sources such as biogas, the dairy cooling sector has the potential to mitigate around 12,000 tonnes of carbon dioxide (CO_2) emissions per year by 2030 (REEP, 2021). Simultaneously, the process of cooling plays a vital role in supporting small-scale farmers and has a direct influence on the availability of dairy products. Consequently, it significantly affects food security, as well as the associated health and well-being outcomes within the nation.

The use of solar electricity in appliances like the example mentioned above can be extrapolated among many other similar operations where battery inclusion can be avoided to maximise the feasibility. Based on data provided by The World Bank, it is observed that a significant proportion, specifically 62%, of the populace resides in rural regions. Additionally, the Department of Livestock Services has reported the existence of around 0.4 million dairy farms, characterised by an average herd size ranging from 10 to 30 cows (WB, 2022). It is worth noting that a considerable number of these farms have challenges in accessing electricity for their farms, hindering their ability to cater to enhance production (WB, 2022). The shades can be used to generate solar electricity which can assist the farming in many ways as mentioned above. This circular economy concept can be used by different agro-industrial practises to maximise decarbonisation at a reasonable rate of return.

7.1.5 Operating Refrigeration and Air-Cooling Systems with Solar Power

Many reasons are pushing Bangladesh towards an unprecedented rise in the use of cooling devices such as air conditioners and refrigeration. The tropical geographical location of Bangladesh causes elevated temperatures (Sarkar *et al.*, 2016), and the wet delta is one of the most humid spots in the world (Bepary and Kabir, 2022), worsening the comfort zone of the dwellers. Global warming and the rise in affordability are also responsible for the rapid rise in air conditioners, fans, fridges, and refrigerators, eventually increasing the power demand. Many cooling devices claim high power consumption, especially if they are lower CapEx models. Air conditioning loads are generally in phase with solar resources in Bangladesh. Every year with the extension of summer due to global warming effects, the country is becoming mono-seasonal with an extremely short winter.

Solar electric cooling uses the sun's heat to create cooling that can be used for air conditioning and refrigeration (Daut *et al.*, 2013). The objective of a solar cooling system is to convert solar energy to electricity and use it in a thermally driven cooling process to lower and regulate the temperature for things like producing chilled water or conditioning air for a building (Oliveira, 2011). The absorption cycle is another promising way of using solar heat for space cooling in domestic and industrial applications where electricity use is not the main concern. However, since this thesis addresses renewable electricity as its primary focus, it will only discuss the electrical cooling methods.

Air conditioners/coolers/refrigerators can be powered directly by photovoltaics or indirect solar air conditioning. Whole-house or whole-building solar energy, which traditionally for most users has also meant net metering to the grid, makes up indirect photovoltaic power for air conditioners (Wang, Han and Guan, 2020). In this instance, solar energy is converted to alternating current (AC) to power the home or building's

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[37] https://www.reeep.org/projects/solar-powered-dairy-refrigeration-bangladesh-enerplus

appliances, including the air conditioner. The benefit is that it is a straightforward implementation because the air conditioners don't require special electronics to accommodate solar. The drawback is that these air conditioners often have poor SEER (Seasonal energy efficiency ratio is obtained by dividing the system's cooling output over an average cooling season by the total energy used) ratings of 14 or below (Reji Kumar *et al.*, 2020). Energy is lost before solar power is converted from DC (direct current) to AC. Since the net-metered building or home is essentially a node on the grid, and utilities must prevent back-feeding power into a dead grid when the grid is down, this disadvantage also means that these air conditioners cannot operate when the grid is down. And now, air conditioners are starting to use DC power like many other household appliances (like TVs and computers). As a result, whole-building solar for such systems must be converted from direct current to alternating current and back again, further decreasing efficiency.

Instead, off-grid solar arrays use batteries to power entire homes or buildings using solar energy. These systems use a voltage controller to control battery charging, after which the battery power is inverted to generate alternating current for the house or structure. They can continue to run after a storm or other event knocks out grid power because they are neither grid linked nor net-metered. To run power remotely to the appliances, the power from the solar panels and batteries must once more be inverted from DC to AC (Daut *et al.*, 2013).

A less expensive partial-power photovoltaic system can reduce (but not eliminate) the monthly quantity of air conditioning electricity purchased from the power grid (and other uses). It is currently cost-effective in residential uses where electricity costs $0.15 per kilowatt-hour (at the 2021 exchange rate). With government subsidies, the amortised cost of PV-generated power can fall to $0.10 per kWh in domestic use. Excess PV power generated when air conditioning is not needed can be sold to the power grid, reducing, or eliminating the annual net electricity purchase requirement (Saha, 2021). However, stakeholders should take solar cooling approaches seriously as the cooling load is increasing rapidly, influencing the base load at a massive scale. They need to frame the policies to favour solar cooling. Currently, the most feasible option is solar power to support the premises where only daytime cooling is required. Government primary schools can be an excellent preference for piloting such ventures. The fans used in those school buildings can be solar powered. The cooling principle is the resource, and the demand are in phase, 'more the sunshine (heat), more the power generated to rotate the fans at higher speed'.

7.1.6 Clean Cooking Outlooks

Biomass burning has always been a major cooking measure in Bangladesh. However, recent socioeconomic progress has expanded the consumption capacity of the people. Many of them are using electricity for cooking nowadays. In particular, electric cookers and stoves are being extensively used countrywide for rice cooking, and the heaters consume a significant amount of electricity. Direct renewable cooking through solar radiation is difficult in Bangladesh when considering cooking regardless of adequate and consistent sunshine availability. The problem of solar cooking's lack of adaptability can only be resolved by maintaining an alternative cooking method (such as biogas burners) alongside solar cookers. Thus, solar cooking may be a significant method of food preparation, but it cannot be the only one (Alam and Chowdhury, 2012). The problem of limited access to sunshine could be remedied by enacting new regulations for urban construction designs that mandate an open area with an adequate amount of sunlight suitable for solar cooking by each family (Alam and Chowdhury, 2012).

Adequate solar insolation and a pressing demand for an alternative cooking energy source are the two prerequisites for the widespread adoption of solar cooking. Bangladesh's vast population constantly demands alternative energy sources (Amuzu-Sefordzi *et al.*, 2018). Even if new gas reserves are discovered in the future, the gas should be used for electricity production and other industrial applications that can contribute significantly to the country's economic prosperity. As previously examined, Bangladesh can use solar cookers for at least 145 days each year (294 days if box cookers are used)(Alam and Chowdhury, 2012). It suggests that solar cooking may be utilised around 40% of the time in Bangladesh. As previously demonstrated, a home can save up to 388 m^3 of natural gas annually by maximizing all sunny days (Alam and Chowdhury, 2012; Aziz, Barua and Chowdhury, 2022).

A study by Aziz et al. (Aziz, Barua and Chowdhury, 2022) indicates that a portion of the population is aware of the necessity of clean cooking for clean indoor air, as they use cleaner fuels and technologies in closed areas, mainly if there are children in the home. However, it appears that the obstacles to adopting cleaner cooking methods are not education but accessibility and cost. As well as urban areas, the region surrounding the capital city has a greater percentage of cleaner cooking. In addition, the electrification rate does not match the adoption rate of cleaner cooking methods. It denotes that infrastructure is more accountable than supply chain mechanisms in clean Bangladeshi cooking (Aziz, Barua and Chowdhury, 2022). Households acquire power connections in places with grid or off-grid electricity, and if there were a widespread supply of clean cooking, it would be adopted more in all regions. Non-urban areas rely on solid fuels, such as biomass, since they are abundant and inexpensive, and cleaner fuels should be made sufficiently economical and accessible to supplant solid biomass. The policies for cleaner cooking in Bangladesh have not kept pace with those for electrification. Thus far, closing this gap is essential for attaining the SDGs on schedule in nexus with cutting down carbon emissions.

The policy amendments demand that appropriate regulations be formulated and enacted to establish a distribution network where solar stoves and retained heat cookers are readily available. The accessories can be supplied reasonably and easily. To promote an equitable business model and eliminate carbon emissions, manufacturers, distributors, and users must be encouraged through incentivisation. Lastly, continuous usage of cleaner cooking solutions must be tracked over time, and peer effects can be mobilised at the community level to encourage new users to make the switch.

7.1.6.1 Retained heat cooking technology

After analysing the present technology of conventional stoves, a locally accessible alternative cooking option, the Retained Heat Cooker, has been developed (RHC). RHC is a non-electrical insulated container designed to reduce the fuel necessary for cooking food. Instead of remaining on a stove for the duration, food is brought to a boil before being transferred to the RHC. Using the idea of thermal insulation, the cooking process is continued without additional heat or fuel. According to laboratory experiments, an RHC can save between 40%-70% per cent of energy, depending on the type of meal. Fifteen entrepreneurs and non-profit organisations have been educated in its production and distribution in Bangladesh. RHC is now provided in 36 Bangladeshi districts. In refugee camps, the Office of the United Nations High Commissioner for Refugees (UNHCR) has distributed 15,000 RHCs[38]. There have been 33,500 units sold to date. It is a proven technology to reduce carbon emissions and many other detrimental externalities from traditional cooking methods. The government needs to promote it.

7.1.7 Not a high-time for a hydrogen-based solution

Hydrogen is being produced by using surplus green electricity. Hydrogen is produced with additional non-nuclear green electricity, including solar power, wind power, or biomass above national or regional grid demand (Agaton, Batac and Reyes, 2022a). The world is moving towards solar-wind power and hydrogen fuel to some extent.

[38] https://reeep.sreda.gov.bd/interventions/energy-efficiency/retained-heat-cooker.html

Some experts recently recommended the government develop a roadmap for hydrogen fuel, creating the misleading narrative that solar power is not feasible[39]. The production of hydrogen electricity is costly on the one hand. On the other hand, it requires an entirely new infrastructure for production, transportation, distribution, and even use. Utilising the thermal energy produced as a by-product also requires integrated ecosystems. Hydrogen will become impractical in Bangladesh's corrupt consumption model without creating an ecosystem. Hydrogen fuel is not a solution to Bangladesh's current energy crisis but a future possibility (Faiz Ahmad Taiyeb, 2022).

When demand is less than the supply of green electricity—in these cases, countries use their excess green electricity to generate hydrogen from water through the electrolysis process, store it, and transport it elsewhere as needed (Agaton, Batac and Reyes, 2022b). The colossal heat energy produced in this process is used for other purposes (Germany). It includes the generation of electricity by making water in the process of reverse electrolysis when and where needed. In other words, it is possible to transport electricity from the country to the continent with the help of technology. But where there is no green power, importing hydrogen from abroad—after building transmission, distribution, and consumption infrastructure—can be a massive waste. Electrolysis is old technology, but the technology has not been commercially developed as it costs much more than the electricity it produces. But hydrogen fuel trends are also developing as solar power, wind power, landfill, or biomass-based power become cheaper (Agaton, Batac and Reyes, 2022a).

The 'energy ecosystem' of hydrogen fuel is not limited to electricity. Using by-product thermal energy and renewable hydrogen supply chains are also included here, such as renewable hydrogen and ammonia industries (La Roche, 1977). European countries have large wind power surpluses; West Africa, the Middle East, and the United States have sizeable solar power surpluses. There is also biomass potential. Some future hydrogen fuel roadmaps are created with surplus green electricity in a few countries (de Bruyn *et al.*, 2020).

Since Bangladesh's green electricity production rate is only four per cent of the total national production, there is no roadmap based on hydrogen fuel import or generation in Bangladesh, which is commercially viable. Therefore, hydrogen fuel technology is not proven feasible for Bangladesh's current energy and power crisis. Still, hydrogen energy may be a future field opening new horizons of possibilities for Bangladesh, which requires more knowledge, research, and investment. Learning and free riding from other countries regarding the R&D may the rational options at present. Only if the solar-wind-biomass power can be harnessed in surplus, it will be the strong rationale for inclusion in Bangladesh's hydrogen roadmap.

7.1.8 Consideration of Urbanisation Propagation

By 2050, 70% of the world's population will live in cities consuming over 80% of the planet's resources (United Nations Projection). Bangladesh is geopolitically divided into 494 sub-districts. Many of these sub-districts now have a current peak load of only 10-15 MW (PDB, 2019).

[39] https://www.thedailystar.net/environment/natural-resources/energy/news/countrys-first-hydrogen-fuel-plant-nears-completion-2227056

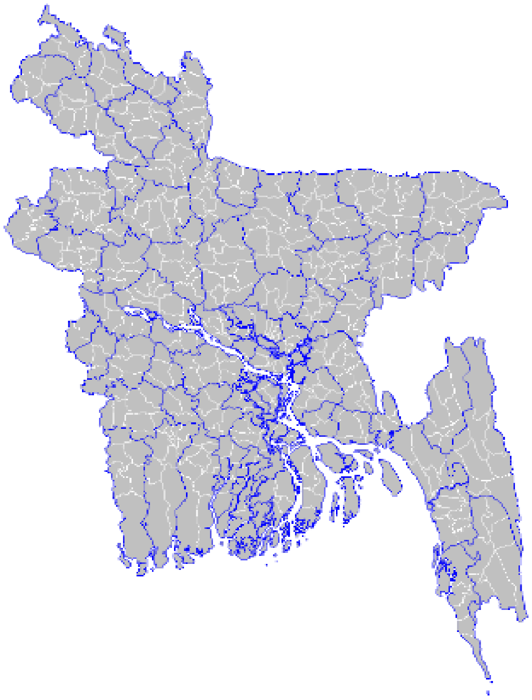

Figure 65 Sub-districts of Bangladesh (White dotted borders) (Centres of 'Village to Town' projects) (LGED, 2018)

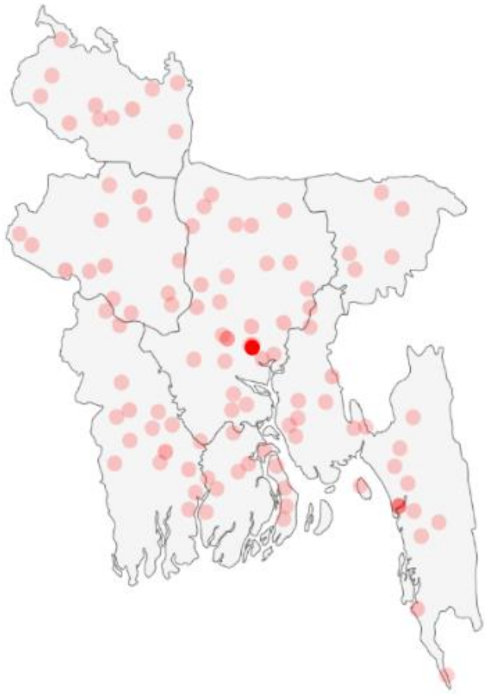

Figure 66 Population density of Bangladesh (The redder, the denser) (LGED, 2018)

The new government recently announced a massive development dispersion and decentralization program named 'My Village, My Town', which includes mini-grid solar park installation projects among several underprivileged sub-districts. Though the demand is presumed to be rising in the future with development diffusion all over the country, this initiative can make a massive leap towards a renewable future. Grid-tied solar power plants braced with partial storage systems may be suitable for introducing the countrywide transformation.

The scheme can have multimodal infrastructural changes in the future. Each subdistrict may have their own separate DC grid in the future, where most appliances would be DC power-driven.

7.1.9 Smart grid augmentation

A smart grid is a modernised electrical grid that employs analogue or digital information and communications technology; it is the key to efficiently utilising many energy resources (Molina Bacca, Knight and Trifkovic, 2020). Renewable energy is a research priority due to its availability, adaptability, and eco-friendliness, and using a smart grid for renewable energy makes it more expensive and promising. This fusion facilitates the efficient utilisation of renewable energies, which is now a significant challenge. Renewable energies can be utilised intelligently and efficiently by utilising smart grids.

Renewable energy development, efficient energy use, and intelligent management systems have replaced fossil fuels, addressed climate change, met energy demand, and raised economic growth (Ringler, Keles and Fichtner, 2016). The distribution of renewable energy in smart grid systems is one of the most important roles in advancing the usage of renewable energy in energy management systems. A smart grid is the envisioned communication network for expanding distributed energy resources such as wind, solar, and hydropower. Many nations are evaluating the usage of intelligent systems as an efficient component for enhancing energy efficiency and addressing the challenges to sustainable development. A smart system, which is a smart meter, establishes a relationship between energy use and consumers through two communication networks. The smart meter is a component of the smart grid systems of the next generation since it can include information technology. By collecting data from users, the providers can utility providers and used to create a more efficient method of advising consumers to use electricity sparingly (Khanna *et al.*, 2020). Using a smart meter to give consumers better feedback or understanding of their energy use based on long-term power users is intelligent. However, it is necessary to incorporate intelligent control to avoid the detrimental impacts of communication latencies.

Many European nations use digital communication technology for the smart grid. Other nations, like the United States, are expanding their smart communication systems (Hossain *et al.*, 2016). Some newly industrialised nations, like Korea and Taiwan, are implementing smart meter systems. Several regions, like Indonesia and Vietnam, are still planning to install these systems. The Australian government has decided to invest 100 million Australian dollars in a smart grid initiative across five sites (Dowell and Pinson, 2016). Their primary objective was to construct a smart city with a chain of new technology energy supply. These projects incorporate intelligent sensors, new back-end information technology systems, intelligent meters, and a communication network. Future motivations include a reduction in peak demand, network dependability, and energy supply with peak pricing, combined consumer, retail, and network sector benefits, large capacity storage, and optimisation of the value of renewable energy sources. These advancements and knowledge may be useful in developing a smart grid transition for Bangladesh.

Beginning in the 1990s, a series of reforms resulted in the formation of the Dhaka Power Distribution Company (DPDC), a power supplier primarily serving the south of the capital city of Dhaka. It is a problem for DPDC to meet the rapidly increasing demand for electricity via its electrical network. In such circumstances, intelligent grids can play a key role. Smart grid systems provide high-quality electricity to all by permitting information interchange between consumers and electricity providers, altering the flow of electricity in real-time, and enabling more effective electrical network management. Francois Lhomme, a project team leader in the Energy Division of Agence Française de Développement (AFD), explains the method in a write-up (Lhomme François, 2020).

Bangladesh's smart grid is in its infancy and comprises solely installing smart meters. AFD (Agence Française de Développement) is strengthening its role as an active participant in searching for and implementing advanced digital solutions in distribution stations and medium-voltage grids through this initiative. The project is financed to approximately 100 million euros, with an additional 12 million euros from the European Union (Lhomme François, 2020). Improved automation will increase the grid's performance, enabling the electricity supplier to optimise energy distribution with minimal expenditure. Thus, it becomes more stable, with no interruptions and more energy distributed from renewable power plants. The plan is to work with the existing network, ensuring it is monitored as it approaches its dynamic limits to prevent consumer blackouts. Smarting the network may be one of the most prominent turning points in the renewable transition in Bangladesh.

Almost all the developed countries in the world are trying to turn their old grids into Smart Grids. It is also important if Bangladesh wants to meet the challenges of 2030 and become a smart-grided country to maximise its renewable adoption rate(Hasan *et al.*, 2017).

In line with the SDGs, Bangladesh must move forward with planning and implementation to switch from the traditional grid system to SG and renewable energy (Maruf et al., 2020). The data shows that most of Bangladesh's renewable energy will come from the solar sector(Halder et al., 2015). Wind energy and tidal energy need to be added to the mix. Also, along with SG and renewables, there should be a way to ensure the infrastructure gets regular maintenance. Bangladesh has already started to move slowly toward a smarter grid system. But a skilled workforce must be put together to implement Smart Grid technologies successfully. This workforce needs to comprise people who know much about the related technologies and have technical expertise.

7.1.9.1 The issues of the capital city

The problem in Dhaka is not the availability of electricity. The issue is more the quantity and quality of available energy vs the growing demand in a metropolitan area whose population is projected to rise from 17 million to 25 million by 2025. This imbalance between energy supply and demand can result in power outages, leading to the use of polluting diesel generators in residential and industrial areas. The smart grid and renewable systems can help address the problem.

7.1.9.2 Why is the smart grid a solution for renewabling Bangladesh in particular?

When the smart grid improves grid performance, it will hopefully reduce the pollution created by the diesel generators utilised as backups during grid failures. There will be a major improvement in the quality of power service for 1,141,000 people. In addition to combating climate change, the project annually prevents 104,000 tons of CO_2 emissions[40].

In general, and not just concerning the DPDC project, the smart grid solution has tremendous operational value. It enables maintenance before equipment breakdowns and optimises equipment usage (power transformers, circuit breakers, etc.). Real-time algorithms that continuously monitor the hardware linked to the grid and increase its life make this possible. The digital control at all levels of the network provides for better awareness of the grid and anticipation of outage-related occurrences.

7.1.9.3 How compatible is the current infrastructure in Bangladesh with this endeavour?

As DPDC works according to international standards and follows state-of-the-art technical criteria, compatibility and interoperability difficulties should be minimal. It means different types of equipment from manufacturers can connect and perform advanced automation activities. Older equipment can be integrated into creative and digital solutions, even if it means updating a few communication components to make the complete system interoperable remotely. It is the fundamental principle underlying the international standard IEC 61850 (Maruf *et al.*, 2020a). Bangladesh is not exempt from this policy.

7.1.10 Solar waste management challenges

Following the entire lifespan, the waste produced from solar panels may become a hazard to the environment of Bangladesh. However, recycling the salvaged modules can change the scenario dramatically. A recent study researched the current position and management after the end-of-life of the Bangladesh solar photovoltaic (PV) module(Tasnia *et al.*, 2019). Solar PV cells have a lifespan of around 15 to 25 years after installation. After the end of life, the solar panel will transform into waste, notably e-waste, which can be an environmental concern in the long run. Hence, assessing waste generation and defining environmentally responsible management is essential. Thus, the study aimed to visualize solar PV cells' current condition, potential waste creation, and management in Bangladesh. It also examined the present waste management policy. The study determined that Bangladesh has a considerable potential to generate solar PV-based e-waste shortly, which needs to be tackled with high priority. Although there are excellent opportunities to

[40] https://www.afd.fr/en/actualites/bangladesh-smart-grids-provide-over-million-people-access-electricity

recover resources from waste panels, there are also opportunities to expand the recycling industry. Regrettably, the government does not have such a plan to date. However, a national plan must be developed to manage this waste stream to a high standard over the long term. The policy may address the following issues:

- The recycling procedure for solar panels is lengthy and complex, and the recycling system chain is still incomplete. Although solar panels do not contain rare earth metals, the positive panel terminals are constructed of silver, which has recycling value. The components contain several other precious elements, such as indium, gallium, and germanium. However, recycling used solar panels presents various challenges, including the emission of solvents during recycling. The ACA (activated carbon adsorption) recycling condensation technology in conjunction with solvent refining may be used (Nahil and Williams, 2011). Then applying a dehydrating mechanism, the produced organic gas can be recycled into a high-purity liquid organic solvent. Subsequently, the procedure can satisfy recycling standards, decrease the release of pollutants into the atmosphere, and save the environment. Even though investing in environmental protection equipment might dramatically increase a company's production expenses, it can also generate economic benefits related to environmental protection (Tasnia *et al.*, 2019). Further R&D must also be funded to determine feasible and sustainable recycling methods in the Bangladeshi context.
- Rare materials are required to construct additional solar panels. The mining and processing of these resources are currently concentrated in a few nations(Turksoy, Teke and Alkaya, 2020). Hence, the solar supply chain is susceptible to disruptions and exploitation (Foley and Díaz Lobera, 2013). The Business & Human Rights Resource Centre has identified human rights violations while mining solar panel materials. In addition, solar panel polysilicon is produced through an energy-intensive process involving forced labour[41]. These revelations have resulted in restrictions against several Chinese solar products. Consequently, recycling will become unavoidable to maintain the solar mission's viability.
- In the future, a more significant proportion of the resources needed to manufacture new solar panels will likely originate from used panels. According to Rystad, recovered silver, polysilicon, copper, and aluminium earn the highest prices on the recycling market[42]. Silver and solar-grade silicon are not typically separated using modern recycling techniques. Together with the remainder of the panel, it is frequently shredded and sold as crushed glass. Fortunately, recycling may soon become more sophisticated because of recent research into how to extract the most valuable materials from photovoltaic panels. Therefore, Bangladesh should not worry more about recycling methods beyond adopting and enacting policies (Tasnia *et al.*, 2019). It just has to initiate, adopt, and implement those.
- Solar started to take off in the 2010s in Bangladesh, and with a lifespan of around 15- 20 years — it is just now approaching the first large wave of disposed solar panels. More materials used to make new solar panels will likely come from castoff panels.

7.2 Regional Renewable Power Grid across SAARC states: The Role of the developed states and overpotent neighbours

Obstacles like land availability and high CapEx of energy storage systems pose strong adversity on the renewable transition pathway of Bangladesh. According to the model, one of the most impactful transition drivers was the imported power from the neighbouring countries. SAARC stands for South Asian Association for Regional Cooperation (SAARC), comprising Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka. A regional supergrid mainly based on the aggregated wind, solar, and hydropower available has been in the thoughts of many policymakers and great thinkers to meet the increasing power demand among the booming states of SAARC. Still, realising such a big dream has been slow because of the

[41] https://www.csis.org/analysis/dark-spot-solar-energy-industry-forced-labor-xinjiang
[42] https://www.rystadenergy.com/news/reduce-reuse-solar-pv-recycling-market-to-be-worth-2-7-billion-by-2030

lack of integrated political will. A renewable regional grid would potentially ensure continuous sufficient green power to the interconnected states by reducing the spatial variability of renewable resources and establishing a solid rationale for regional geopolitical stability. Many states have an excess of hydro, solar and wind energy potential. They can safely feed their surplus power to the proposed interconnected grid to ensure a smooth and reliable flow across the state boundaries.

For example, Bhutan has no petroleum or natural gas reserves but has oversized hydro potential estimated to be over 30 GW. At present, India supplies about 2000 MW of power to Bangladesh. Nepal and Bhutan agreed to export 5000 MW of electricity to Bangladesh, 2,000 MW each from the Saptokoshi project in Nepal and the Sankosh project in Bhutan (Asia, Lanka and Mahmud, 2012). Bangladesh is already interconnected with India through a High Voltage 400kV DC line between Bheramara (Bangladesh) and Baharampur (India), transferring around 1160 MW of power. Bangladesh will likely be linked with Bhutan, Nepal, and Tripura (India) 's envisaged grids and with Myanmar and Thailand through the Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC). Based on the current efficiency and reliability, Bangladesh cannot transition to 100% renewable depending on its local resources only to meet future demand. This section discusses the availability of green energy potentials among the SAARC states and the techno-economic practicability of constructing a Regional Power grid for that Region.

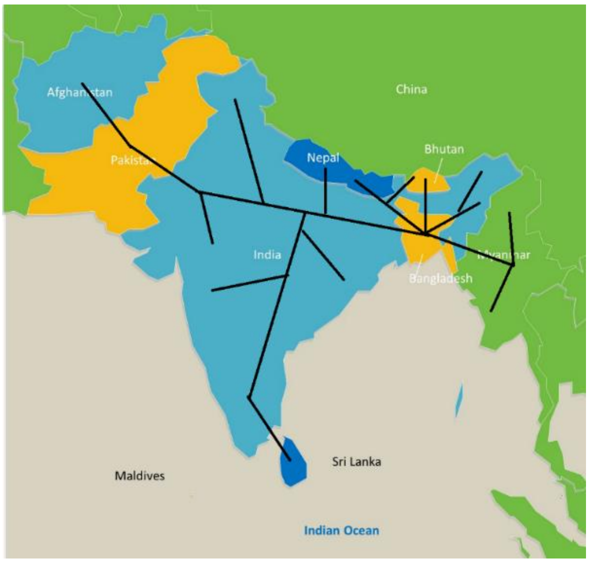

Figure 67 An illustrative diagram of a SAARC supergrid

The main obstacle to a complete transition towards green power is the poor reliability of renewable resources due to the intermittency of energy supply from such sources (Lofthouse, et al., 2015). To ensure incessant supply, three solutions are available: geographic Dispersion of renewable power plants, expensive storage and curtailment of excess generation (IEA, 2015). Considering the most optimum option of widespread interconnected Dispersion assumed to disentangle many concerns about renewable energy technology, this section probes into the visionary approach of future power generation and distribution through an electric transmission network.

The perception of a regional renewable electricity grid includes the contexts, paybacks, and considerations of diversified and irregular dispersions of renewable energy spots around a vast region. They profoundly influence the goal of inclusive, sustainable energy access and distribution for future generations. A renewable electricity supergrid can be envisioned as an integrated setup comprising intracontinental, intercontinental, and universal backbone interlinks as well as the power grids (installation, generation, transmission and distribution and management of the very large scale and other renewable power systems) in all interconnected countries (Gellings, 2015).

7.2.1 Renewable Potential and storage prospects of SAARC states

SAARC states are situated around a widely geographically diversified region where many forms of renewable energy can be harvested for generating electrical power. Being situated around the tropical and sub-tropical area of South Asia with the extensive mountain range of the Mighty Himalayas, this Region is blessed with enormous solar and hydro energy and moderately with wind energy. In reality, each of the SAARC countries is highly potent in renewable energy resources of various kinds. Some countries like Bhutan, Nepal and India are enriched in hydro, while some, like India and Pakistan, are enriched in consistent insolation. Afghanistan is endowed with the world's largest Lithium reservoir, crucial for ensuring a reliable and stable renewable energy storage system. This section will briefly focus on some of the most Renewable Rich Locations.

7.2.2 Solar and wind potential of India and Pakistan

India's energy consumption has been increasing rapidly. Considering the growth rate, solar energy has become India's fastest-growing energy resource. Rajasthan's desert zone has a massive energy potential from daily insolation. The Thar Desert covers 66.67% of the complete area of Rajasthan. The semi-arid atmospheric condition of Rajasthan makes it absolute for efficient solar power generation. The climatic condition of Rajasthan causes it suitable to undergo approximately 330+ bright days per year and 6.1 to 6.5 kWh/m^2 sun radiations per day. The average atmospheric temperature of Rajasthan is between 35 to 41 degrees, and on summer days, it crosses above 45 degrees. Rajasthan can have an installed capacity of 300,000 MW from only 15,000 Km^2 of land area. Till January 2017, the solar power generation capacity was 16,000 MW[43], ranking the state first in India (Yadav, 2023).

India's economy is growing rapidly at an average GDP growth rate of ~8% (2022) [44]. Energy is key to achieving India's development goals, supporting a rapidly developing economy, bringing electricity to those who remain without it, and developing the infrastructure to meet the needs of the world's most populous country. As of Feb 2023, renewable energy sources, including large hydropower, have a combined installed capacity of 174.53 GW[45]. India's pledge at the climate summit (COP 27) stated the country's intention to follow "a cleaner path than the one followed hitherto by others at a corresponding level of economic development". To this end, India has established goals to expand its use of renewable energy and more efficient technologies. India's well-developed wind power industry has the capability and experience to help meet the country's climate and energy security goals. Today India is the 4th largest wind market globally, with total installations crossing the 82 GW mark at the end of March 2022. Various mapping in India has already demonstrated a colossal amount of wind potential that can largely contribute to the SAARC renewable grid (Yadav, 2023).

Pakistan has great solar power potential because the sun warms the surface year-round. A study used fifty-eight meteorological sites nationwide to find solar energy potential. Angstrom equation and Hargreaves formula calculated monthly solar energy potential using monthly climate data of bright sunlight hours, mean maximum and minimum temperatures. The results show that solar radiation intensity greater than 200 W/m^2 was observed from February to October in Sindh, March to October in almost all Balochistan regions, April to September in NWFP, Northern Areas, and Kashmir, and March to October in Punjab. In December, Cherat had 76.49 W/m^2 of solar radiation and Gilgit 339.25 W/m^2 (Abdullah *et al.*, 2020). The average monthly solar

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43 https://www.business-standard.com/article/current-affairs/solar-energy-generation-capacity-touches-16-000-mw-in-rajasthan-122121500818_1.html

44

45 https://www.investindia.gov.in/sector/renewableenergy#:~:text=Renewable%20energy%20sources%20have%20a,Wind%20power%3A%2041.9%20GW

radiation intensity in Pakistan ranges from 1500 W/m^2 to 2750 W/m^2, notably in southern Punjab, Sindh, and Balochistan. A study concluded that 2.8×10^6 GWh of power could be generated yearly in Pakistan from grid-connected and off-grid PV systems (Khatri *et al.*, 2022).

7.2.3 Hydropower Potential of Nepal and Bhutan

Nepal's hydropower applicability can be viewed as almost ideal. At least 70,000 MW of hydropower is technically and economically feasible out of almost 90,000 MW. Nepal can sell over 80% hydroelectricity to SAARC neighbours to meet its demand. SAARC grids can supply green energy to networks that are constrained. India and Bangladesh are talking with Nepal to invest in huge hydropower projects. Northern India and Bangladesh need lots of power to prosper economically. Nepal should partner with India and Bangladesh on hydroelectric projects requiring large investments. It could boost SAARC grid construction. It will peacefully develop Nepal's hydropower and negotiate power purchase agreements with India and Bangladesh for continued power trade. (Alam, 2017).

With its abundant hydro resources, Bhutan has a total techno-economically exploitable capacity of 30,000 MW (Energy Sector Management Assistance Program (ESMAP, 2007)). However, the currently installed capacity is 1,490 MW, approximately only 6% of the potential total. Bhutan has four major rivers: the Torsa, the shortest; Sunkosh – the longest; and Wangchu. Lake Manas is also to be counted. These rivers run almost dry during the winter but attain very high flow rates in monsoons (Dhakal, 1990). In addition, other smaller rivers originate in the Middle Hills. The Middle Hills have no permanent snow or ice but receive heavy rainfalls throughout the monsoon. These two countries can be significant contributors to the SAARC renewable power grid.

7.2.4 Lithium reservoir of Afghanistan

Renewables' spatiotemporal variability is one of their biggest limitations as baseload suppliers. Energy storage devices like batteries are essential for reliability in distributed renewable power systems, even though interconnection will lessen its necessity. The digital, low-carbon economy needs lithium. Although lithium is a "rare metal," its crustal average is 35 ppm. Lithium was previously used only in specialised markets in glass, ceramics, high-temperature greases, and chemicals. Over the next decade, demand for this "rare metal" will rise as electric cars use lithium batteries supplies match demand. The global demand for EVs has increased exponentially for a couple of years. The forecasts denote the demand may surpass the supply very soon (IEA, 2023). Afghanistan has enough main raw materials to make enough batteries to steady the grid. (Fritz, 2022).

7.2.5 Can Regional Energy Grid put an end to the 100% renewable debate?

In a feedback to Jacobson's 100% worldwide renewable proposal (Jacobson *et al.*, 2015), Clark et al. (Clack, et al., 2016) pointed out some errors in the proposal namely "(a) several modelling errors presented that invalidate the results in the studies, particularly with respect to the amount of hydropower available and the demand response of flexible loads (b) poorly documented and implausible assumptions, including the cost and scalability of storage technologies, the use of hydrogen fuels, lifecycle assessments of technologies, cost of capital and capacity factors of current technologies, and land use (c) the studies' lack of electric power system modelling of transmission, reserve margins, and frequency response, despite claims of system reliability (d) Lastly, it was argued that the climate/weather model used for assessments of wind and solar power production has not shown the capacity to accurately simulate wind speeds or solar insolation at the scales needed to assure the technical reliability of an energy system depending on so strongly on such intermittent energy sources" (Clack, et al., 2016). In the next paragraphs, some ways outs have been discussed.

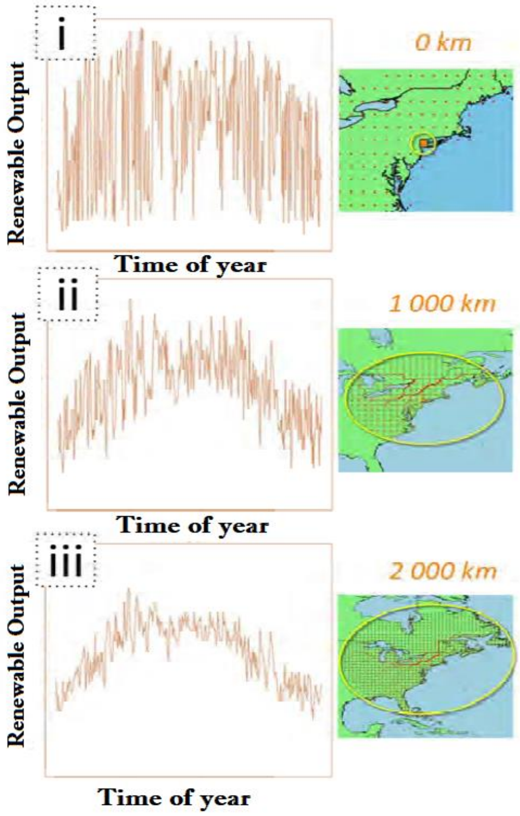


Figure 68 The smoothing effect of Solar output variability by interconnecting the spatially dispersed output points (Perez, 2014)

In response to the first argument, it can be considered that the option of Hydropower is not indispensable for the large grid and can be substituted by modifying the size of the desert VLS-PV (Very Large Scale PV) plant capacities successfully because the smoothing effect becomes so high. In 2014, Perez & Fthenakis underpinned the effectiveness of geographic Dispersion and interconnection as a variability-mitigating strategy. They deduced that at shorter periods, weather and atmospheric conditions induced solar variability correlation between two distinct geographic locations decreases with spatial extent. Mathematically, the aggregated variability between N interconnected spots decreases exponentially as $1/N^{1/2}$ (Perez & Fthenakis, 2014) (Figure 68). Such a vast abundance of solar power allows the substitution any other forms of renewable energy when deemed necessary. Since plenty of unused land is available in the desert, and only 10% of that landmass can generate enough electricity to empower the entire world, with a smart grid integration system, it is not entirely impossible to go 100% renewables, at least in the case of electricity.

In response to the second claim, it is to be noted that as a result of the wide Dispersion of renewable sources with the extreme RES among the spatiotemporally insolated deserts like Thar or Baluchistan and potent windy and hydro locations across the subcontinent and establishing HVDC interconnection among them, the need for bulk storage can be reduced by 90% (Perez, 2014). Moreover, there is no denying that storage technology is improving rapidly in the case of individual transports like battery-driven electric cars. The Lithium abundance in Bolivia and Afghanistan can sufficiently meet the regional demand for high-class lithium-ion deep-cycle batteries for individual transports (Bradley, et al., 2020). Public transport like trains, trams, and cable cars are electrified without battery usage. Therefore, the issue can be solved by constructing a multinational energy grid to ensure the continuous flow of green energy with minimal storage systems.

In response to the next point, digital modelling can be modified and amended to respond to any situation. Moreover, the interconnection efficiency, integration and interblending among the regional networks can be improved through cutting-edge technological devices and systems. The next section of the thesis will try to focus on that issue.

The final point argued about the high unpredictability of renewable powers. The unpredictability of renewable energy sources like solar and wind is one of the most important considerations when evaluating their contribution to the grid and its economics. In the case of a regional grid heavily dependent upon desert VLS-PV or large hydropower plants, the insolation prediction remains precise due to particular desert environment features already discussed in the previous sections. Moreover, there are other techniques to simulate the wind speed or insolation with considerable accuracy that are supposed to improve more and more incrementally every year. Whatever the technique is, the interconnection among the widely dispersed power spots undeniably results in an incredible capacity to ensure the incessant flow of energy at a consistent rate (Perez, 2014) which refers to the augmentation of the reliability of renewable energy. It has been discussed in detail by Botterud (Botterud, 2014), considering the problems encountered practically in ensuring correspondence between the fluctuating supply and largely steady[46] demand. This chapter discourses on issues relevant to the difficulties which arise principally because, unlike conventional electricity generation methods, i.e., thermal or nuclear power plants, since the source of renewable energy is an extremely complicated function of a countless number of factors and variables, the output cannot be estimated at a future time with an adequate level of reliability.

In an extensive and pertinent study, Botterud points out several pragmatic ways to solve the predictability problem (Botterud, 2014). In that quest, based on evidence and regressions, he advocated that the pricing and distribution of the generated power are intricately related to the accuracy of predicting how the production will vary with time. When a high degree of unreliability is attached to the forecast, the producers are forced to increase the reserve's capacity or alternative sources that offer more reliability so that the inconsistencies, as they arise with time, can be handled easily (Botterud, 2014). The results show that computer science enhances humans' ability to construct numerical weather models. Superior statistical methods have also helped the renewable energy business. Measurement and data management methods also advance rapidly. These provide a more flexible numerical assessment of power demand, generation estimates, and markets. According to the author, such advances are linked to electrical appliance energy efficiency, distribution techniques, new technologies, storage systems, and more. Thus, renewable energy availability can now be globally predictable (Botterud, 2014). It endorses the technical rationale behind the regional power grids reinforced with renewables.

7.2.6 Smart Grid Application for Derisking the Cross-border Grid

This section focuses on another crucial issue of a large, interconnected grid: grid security and risk minimisation through the most recent de-risking technology, namely smart grid operation. Energy security is another big challenge in the nexus of constructing a regional grid where regional blackouts may occur due to natural calamity or subversion. Nonetheless, today's smart grid technology can potentially handle the issue. M. A. Islam et al. discuss in detail the definition, need, characteristics, comparative superiority to the conventional grid system and hurdles to successful implementation of the regional smart grid approach based on renewable energy sources in their paper (Islam, et al., 2014). The paper contains a significant amount of statistical data which illustrates the feasibility of the concept of the intelligent grid system while portraying the intensity of the interest that there is in it, especially in the developed world. The authors presented rudimentary statistics showing how regional electricity generation is divided among different methods and fuels. This technology seems to become noticeable and one of the main components of future regional grids to handle the fluctuation and distribute power uniformly in a digitally programmed way.

The smart grid can be defined as integrating different sources so that they can all feed in and consume at the same time at the most optimum combination to produce the best rate of return in the same grid. In other words, the discrete existence of power plants, irrespective of their type and fuel used, is to be eliminated at

[46] When the term steady is used, it is intended to mean a comparatively easier predictable temporal pattern.

the supply level. While productions will be individual, the distribution will be through a standard system which the authors term an intelligent grid. It is little more than a power management strategy. The primary benefit of this approach is that it can harness the benefits of renewable energy sources while eliminating the accompanying disadvantages, i.e., their unpredictability and lack of consistency. Combining different sources makes it possible to devise a grid system that will comfortably supply the power required for commercial and industrial sectors while also satisfying residential needs (Maruf *et al.*, 2020b). The goal appears to transfer the pressure on fossil fuel sources to renewable ones. Renewable energy sources can address the issues of fluctuations and unreliability if they are connected and integrated into one standard system, even though it is impossible to gainsay that the contribution of fossil fuel might be difficult to compensate for. The most attractive and ground-breaking trait of the smart grid concept is that it has the potential to be truly international. Electricity produced in Sahara can be used to light areas, not in the proximity of the desert, known for its solar potential. One region's abundance can alleviate the shortage in another, and seasonal fluctuations can be used to direct the energy current in suitable directions.

Real-time operation and distinct responses to each end user's request are features of the smart grid. A load forecasting methodology can determine how much power a specific home, business, sector, area, or state needs daily. The central system can react immediately to changes in load. The central system monitors and controls individual stations flowing into the system. In other words, the load pattern analysis allows for directly determining the operating parameters of a wind farm or a solar station from the central system. The best way to explain it is probably as two-way communication. The smart grid acts as an intermediary body in the information flow between producer and consumer entities, ensuring that it is efficient and meaningful.

Broad and Dragoon (Broad & Dragoon, 2014) proposed another appealing idea for managing the fluctuating power characteristics of a wind farm. It is well known that wind turbines offer an extremely attractive means of harnessing power to generate electricity. However, an inherent difficulty is that the power generated is as unstable as the wind speed and direction. Therefore, it is difficult to devise a strategy allowing wind farms to feed the main grid directly. Despite employing a powerful and efficient method, however, it is seen that it is difficult to avoid introducing fluctuations into the main grid once the integration is done. An interconnected grid can solve the issue substantially. However, interconnection can smoothen the aggregated outputs but cannot eliminate the probability. Therefore, the entire grid must be supported with capacitor banks or energy storage systems to derisk the chances of wide blackouts.

The idea Broad and Dragoon propose is based upon recognising that while the generated power fluctuates, so does the load itself. Therefore, these opposing fluctuations can be used to counter one another, alleviating the disturbances introduced into the system. The writers acknowledge that there are more attractive methods of achieving a smoother power curve in the main grid. Introducing a gas turbine, for example, for a diesel power station, will be able to deliver the same result efficiently. However, these are highly costly alternatives.

The authors mention a Princeton University program which, like what is suggested by the authors, was able to manage the load using such efficiency that the requirement went down by over 90% (Broad & Dragoon, 2014). While the authors recognise that implementing this system will require a significant amount of change to be introduced to the existing system, there is no denying that the advantages outweigh the comparative disadvantages. The cost of the required transformation the system must undergo is insignificant compared to the benefit to be gained. The Advanced Meter Structure or AMI can be utilised to identify the consumers and the types of appliances ideal for this new technology. Lastly, they underscore the importance of formulating friendly and encouraging policies to make the required transformation possible.

7.2.7 Challenges

The primary factor in the effective execution of cross-border power trade is the establishment of multilateral regional cooperation among adjacent nations, which is crucial for guaranteeing equitable conditions (Amin, 2020). This aspect is primarily non-technical in nature. Despite the challenges posed by the volatile and self-interested behaviour of regional major powers, it is imperative for Bangladesh to assume a leadership role in initiating conversation through various venues, such as SAARC and BIMSTEC, to safeguard its own interests. In order to establish a unified synchronous grid, it is imperative for countries within this region to enhance their investment efforts towards bolstering their grid infrastructure. This should be done through the implementation of a consensus-driven investment strategy, prioritization of supportive projects, and the adoption of an incentive-based maintenance policy (Amin, 2020). Additionally, the establishment of additional grid interconnections can be facilitated by the promotion of joint venture investments.

The neighbouring countries of Bangladesh, including India, Nepal, and Bhutan, possess substantial reservoirs of renewable potential. Bangladesh has the potential to engage in resource exploration in many nations and undertake feasibility studies to assess the economic viability of such endeavours (Hossain et al.,2020). Currently, there are only two grid connections that are accessible, namely Baharampur – Bheramara and Suryamaninagar, Cumilla. The difficulty is in enhancing the existing grid structure and promoting greater grid interconnectivity to facilitate cross-border electricity exchange while adhering to international standards.

Furthermore, it is imperative for nations to reassess their policies regarding the utilisation of transmission grids in order to facilitate the advancement of trilateral or multilateral power trading (Hossain et al, 2020). The governments of the individual nations should be incentivized to reassess their fuel mix policy and energy exchange policy in order to facilitate and encourage cross-border power trade within this region. Moreover, to effectively harness and explore energy resources, it is imperative for the governments in these regions to establish a cohesive legislative framework and regulatory system (Hossain et al., 2020). In order to establish a consistent legal framework and regulatory system, it is possible to draw upon existing European and African frameworks and laws (Hossain et al., 2020). Therefore, through the active involvement and collaboration of the neighbouring nations, the expansion of this trade can be facilitated, reaching as far as Thailand. Such an expansion would have significant implications for economic growth, the reduction of carbon emissions, the optimization of energy production and consumption, the establishment of a robust alliance, and ultimately, the promotion of regional prosperity, which undoubtedly encompasses Bangladesh's equitable participation (Hossain et al.,2020).

7.2.8 Initialisation and steps forward

It is now understood to be a well-established fact that the SAARC renewable energy grid is impossible to materialise in the absence of regional cooperation and geopolitical partnership. From this perspective, it is essential to consider the probable focal points of the concept in a strictly geographic sense. One can consider India a suitable candidate, having accomplished pioneering milestones in developing and deploying very large-scale photovoltaic plants, setting up massive wind and large hydroelectric power plants, establishing the smart grid technology and, most importantly, the High Voltage Direct Current technology. The exploration and harnessing of its solar, hydro and wind energies are characterised by the enviable potential in Northern India and expansive hydroelectric projects in the country's Southern parts. In an aim to meet the demands of a 1300 gigawatt, principally due to a continuously expanding industrial sector in the Southern and Eastern zones, the Indians have one of the largest electricity distribution networks in the world now. A few years ago, well over US $37 billion was invested in these infrastructural measures, and it is reasonable to expect that such expenditures will remain the norm for several years. According to the estimates of an international body concerned with energy affairs, several trillion more dollars must be invested for the renewal and modernisation of the transmission and distribution infrastructure that the country has. A high-ranking official at a research institute engaged in active investigations into India's opportunities in the fields of renewable energy and smart-grid technologies has stated that grids connecting India to several other regions of the world, particularly China, Europe, Asia, the Middle East, and Africa, are currently being considered with great enthusiasm and care. Considering the complexity of European power generating and distribution technologies, a Euro-centric energy grid has been a possibility for some time. A European institution has been tasked with investigating the feasibility, bureaucratic, political, and technical prerequisites for implementing such a vast grid. SAARC grid may be a sufficient first step in achieving it.

Fundamentally speaking, the general concept is to develop a SAARC supergrid that will connect the member countries. Activists and lobbyists have already engaged themselves in the persuasion of the governing bodies across Europe for the inauguration of such a project. A German researcher's work pertinent to the supergrid concept has indicated that if such a grid does materialise, its supply will be dominated mainly by wind power. At the same time, the other renewable energy techniques contribute only on a small scale.

For example, a handful of European projects have already culminated in success in planning and execution. For example, one costing several billion Euros established a supply link between zones producing excess power and those unable to meet their demands in Germany. Another project set up a similar transaction between Germany and neighbouring European countries. France also entered a partnership with Spain in a much similar manner.

The findings show that multinational grids require new market and value appropriation throughout the electricity value chain. No global power or method exists to resolve conflicts and trade-offs; hence there is no clear solution. The global Super-grid raises geopolitical issues. The development of dependencies and the need for global standards may not lead to a system that automatically generates benefits for all, as Buckminster Fuller (Ananthasuresh, 2015) dreamed, but to a system dominated by a few powerful actors that generate economic and political benefits for some. Governments have used electricity networks for commercial and political ends throughout history.

If the required political amity can be attained, one of the biggest hurdles will be financing such a project. Predicting the actual cost of such a massive and genuinely international project is a tremendously difficult task. Still, those espousing the idea are indeed right in pointing out that the advantages justify the expenses. It was suggested in a journal paper (Ernst, et al., 2013) that an undersea cable for transmission of three gigawatts of electricity spanning under six thousand kilometres may require just about two million US$ for installation for each kilometre while the terminals were estimated at around three hundred million US$. However, the ultimate delivery of electricity will be possible at a much cheaper rate since the consumers will have the luxury of buying electricity from the cheapest available source.

Several times, it has already been indicated that there is no way of preventing the need for an international consensus based on trust and cooperation. It has been suggested that in trying to enforce a flux of interest towards renewable energy, there is no alternative to imposing taxation on energy sources with direct or indirect negative consequences from the point of view of natural welfare and protection.

While financing happens to be a significant problem, it also must be recognised that governments and regions must agree on pricing and distribution policies. Those negotiating the deal must have technical competence and sound knowledge of financial transactions.

Above all, on our way towards the materialisation of a SAARC supergrid, all involved must create a common international platform for technical transactions. At the same time, the finance policy and business itself must be formulated with exhausting details. These policies should contain definitions of all relevant to the security, operation, maintenance, and uninterrupted operation.

There is no doubt at all that a SAARC green supergrid is not a simple undertaking. It is likely to be one of the largest, if not the largest, examples of human cooperation if it comes into being. What must be acknowledged is that even if the cost of financing such a scheme is colossal, there is also no rationale to continue to burn fossil fuel.

Energy cooperation is one of the most critical drivers leading to durable peace and prosperity in the Region. SAARC Energy Centre (SEC) was created through Dhaka Declaration, in 2005, as the particular purpose vehicle for realising the vision of SAARC leaders to establish an Energy Ring in South Asia. It started its journey on 1st March 2006 in Islamabad, Pakistan. SAARC energy cooperation program provides a central substantive element for the economic prosperity of South Asia towards satisfaction of the energy demand of the Member States. SEC is converting energy challenges into opportunities for development. It is the platform involving officials, experts, academia, environmentalists, and NGOs to tap potential cooperation in the energy sector, including developing Hydropower, renewable and alternative energy, promoting technology transfer, energy trade, energy conservation and energy conservation and efficiency improvement in the Region. This regional institution of excellence for initiating, coordinating, and facilitating SAARC initiatives in energy enables the stakeholders to come together to meet the energy challenges faced by the SAARC Member States. Institutes like this can play a primary role in the integration and coordination among the states.

Along with discussing the feasibility of an ultimate renewable transition, the thesis also tried to refute the criticisms against 100% renewables by applying recent cutting-edge technologies like smart grid and digital optimisation technologies and precise prediction methods. The derisking of a regional blackout can also be implemented with innovative grid technology, the peak demotivating factor against such a project. However, more profound, comprehensive, and extensive studies should be conducted to deeply probe this colossal step towards a sustainable power future. The risks associated with such a colossal project should be considered, enumerated, and assimilated into the research. The international research and expert groups and the business and continental political leaders could also actively participate in handling the emerging challenges and develop the required approaches and techniques to facilitate the SAARC Renewable Power Grid. In light of the analysis, it can be inferred that the optimal utilization of interconnection projects among South Asian nations would be achieved through the implementation of a market-oriented approach to cross-border power trading, complemented by a region-wide regulatory framework that effectively enforces stringent economic discipline.

7.2.9 Comparison between model and opinions

According to the model, if some crucial influencing variables move as projected, Bangladesh's accelerating sociotechnical capacity will allow its power sector to go 90% green by 2060. By 2050 it will have the capacity to exceed 300 TWh, a remarkable milestone. If energy conservation and saving schemes and systems are adopted and enacted, it may be sufficient to meet all the demands considering a partial diaspora due to future migration. However, the interviews and surveys expressed many challenges and pessimism embarking against such aspirations. Most doubted the possibility of 100% greening; even, if possible, the sun would not show up before 2090-2100 (Figure 69). The model parameters were adapted to reflect the responses from the interviewees. It shows the impact of applying current stakeholder responses (red) compared to the projected prospects (green). The responses were inserted into the model by varying the upper limits of several variables according to the responses of the interviewees.

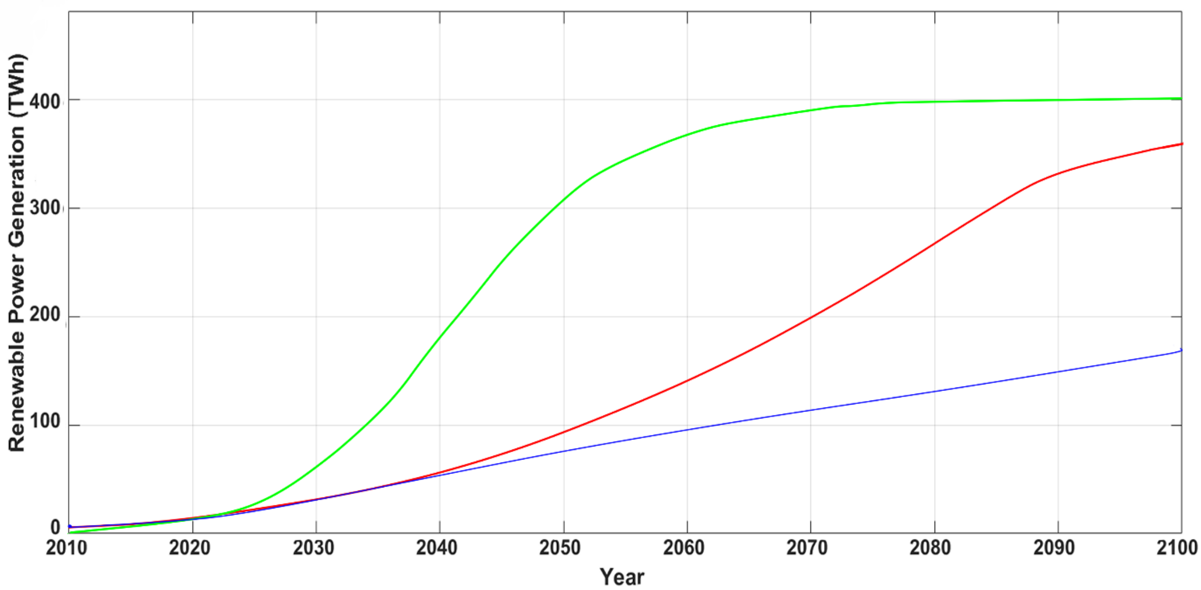


Figure 69: Three different scenarios of possible transition pathways (-----Capacity Modelled outcome ----- Business as usual ----- Interviewees' opinion)

Though the future is uncertain and depends on several dynamic variables interacting, it has been found that many system transitions took place earlier than expected (Heilig et al., 2017). Several mutative factors are effectively pushing the transitions forward. Few of them were not even foreseen. For example, one of them was the price hike in fossil fuel due to the recent Ukraine-Russia war. Europe's energy arena predominantly ran on gas, coal and oil from Russia and Norway. Affected by a sudden energy bill surge, people worldwide reasoned that local resources should address, endorse, and ensure energy security (Browning Noah, 2019; Thomson Ewan, 2019). According to a report by Whiston, In Australia, within just one year, rooftop solar modules and batteries sales surged up to 7.5 times that of the previous year (Whitson, 2022). The same source informed that thirty per cent of the houses got solar systems to cut down energy bills, and the number is rising exponentially. Bangladesh was also nudged by the shock and compelled to adjust its imported fuel price (Alo, 2022). The policymakers have also taken the issue seriously and are getting motivated toward renewable capacity augmentation locally to mitigate the stress (Star, 2022).

There have been several dramatic signs of progress in Bangladesh in the last few years regarding renewable resource power generation. As per the model prediction, the exponential `take off` period has started. Within a few months, several solar power facilities will begin operating nationwide. In addition, a few wind farm preparations are well underway (Government *et al.*, 2021; Bepary and Kabir, 2022). The policymakers are hopeful that the share of renewable energy in the power sector will rise steeply during the next few years (Nasrul Hamid, 2022). There are now 23 renewable energy power stations in various phases of development. These plants' total solar power peak capacity is expected to exceed 1,550 MW. The country's largest solar power facility near Mymensingh's Gouripur is already wired into the national grid. It has a 73 MWp power generation capacity. Bangladesh's humid and mild environment annually provides more than 2500 hours of exploitable sunshine. The project is situated in Mymensingh's Gouripur neighbourhood along the banks of the Brahmaputra River. The project's 173,000 solar panels and 332 inverters will add ample power to the country's main grid. Solar power poses no risk of environmental damage; hence, environmentalist groups endorse it. Solar power prices also decrease per unit everywhere, endorsing the model prediction. Grid-tied Solar power is currently more affordable than fuel oil if consistency is not considered. Therefore, interest in investing in harnessing renewable energy is increasing. There are over 137,000 persons working in Bangladesh's renewable energy industry. Bangladesh is ranked fifth out of 161 nations in terms of the number of people employed in the solar power industry (International Renewable Energy Agency and

International Labour Organisation, 2021; Sajid Yeamin, 2022). Not only is the use of renewable energy increasing, but it is also helping the economic zones to prosper homogeneously.

The country's largest solar power plant, the Teesta Solar Power Plant, started operating in April 2023. It has a maximum generation capacity of up to 280 MWp. 350 GWh of electricity will come in a year, amounting to the price of around 2500 million takas (~25 million US$, April 2023 exchange rate). The project used an investment of 170 million US$, and the payback period is expected to be six years. It will be a phenomenal leap in developing the country's solar power and contribute to an exponential transition rate (Alo, 2022).

Therefore, several signs demonstrate quite an optimistic scenario for the future growth in renewable power generation in Bangladesh. However, according to the model, the turning points for the mass-scale deployment of green power plants will depend on a few crucial factors. The model simulations exhibited that foreign grant is still vital in Bangladesh's green power generation. Efficiency and performance are other significant influencers. The efficiency of solar modules is increasing over time and will more in future (Wazed *et al.*, 2018). The Bangladesh government has imposed provisions to control the quality and longevity of the devices to ensure a reasonable rate of return from renewable business.

Nevertheless, there are still a lot of gaps between the forecast and the range of optimism among the stakeholders. The next chapter will attempt to focus on how to close them. It will take up every variable considered in the model and explore the prospects of the available options to maximise its influence in favour of compelling the transition.

7.2.10 Addressing the dilemma regarding the preference of policy option

Exactly what kind of renewable power system should Bangladesh prefer to deploy? What system will be the most feasible for the Bangladeshi context? These questions are somewhat challenging to address in brief as they are connected to several multifaceted, interconnected variables. With lower affordability, the country must focus on cheaper options to initiate its transition ventures. The principle of the transition policy should be commensurate with the central theme of the transition model's conceptual frame: " As the country prospers and enhances its sociotechnical capacity, it will afford more sophisticated systems and methods to generate more green power". For example: when battery or capacitor price becomes feasible and affordable to Bangladesh, the country will go for baseload generation from renewable. Adding sophisticated energy storage systems can ensure the reliability and consistency of such systems' electricity.

Harnessing wind has many challenges in Bangladesh and has not been proven affordable (Jacobson et al., 2018). The study has already conducted an extensive literature review on Bangladesh's prospects and abundance of renewable energy resources. According to these, solar is the most viable and extensively exploitable renewable energy source. Though mass deployment of solar power has many difficulties, there are more critical challenges in using biomass, hydro, geothermal and tidal too. Therefore, Bangladesh has already decided on the preference ranking regarding the solar resource it would pave its transition pathway (Chowdhury, 2021). Policymakers and other stakeholders also opined coherently in the interviews and surveys conducted in this study. However, suppose off-shore wind technology displays some giant steps in cutting down the installation cost across Bangladesh's cyclone-prone coastal belt. In that case, it may consider the option in the future following such an achievement. Till then, Bangladesh must wait and depend on the outcomes of ''research and development'' programs ongoing worldwide.

7.2.11 Addressing the affordability issue

According to the model, the renewable emergence in Bangladesh was highly supported by foreign aid, grants, and support to date when the country could not deploy it sociotechnically. However, though the number of external grants and aid may fall, the scope and motivation towards foreign direct investment may also rise due to the country's future economic affordability and sociotechnical capacity escalation. Escalated affordability brings multifaceted multiplier effects on a country's socioeconomic and financial domains, including wider scopes for further improvements in all sectors. The development trends and indices have shown promising signs in the last two decades. The enhanced sociotechnical capacity and developed infrastructure reinforced with the improved security status of social safety nets will attract foreign investors. The steady progress in sociopolitical stability also enhances reliance among foreign investors enhancing their investment security and attractive rates of return.

Upon graduation from LDC (Least developed countries) list, Bangladesh will likely lose ‘’tariffs and tax exemptions’’ in many exporter countries(UN General Assembly, 2021). Moreover, the flow of non-returnable grants and aid will eventually slow with many other financial advantages the low-income countries enjoy regarding trade and commercial exchange between them and the developed countries. Summarising all these, Bangladesh may compensate for the deceleration in grants or generous charity flows in a few ways:

1) *Widening own budget allocation for renewable expansion:* If the flow of grants slows down, private and public agencies must expand the budget allocation in the renewable power sector. The steady growth of the affordability of the government and private farms enhanced the capacity for transition. However, an optimisation trajectory is needed to determine the rate at which Bangladesh has to expand its renewable budget as foreign aid and grants drop. Suppose, by 2030, Bangladesh has a target of 50 TWh of renewable electricity. However, only 30 TWh could be generated with the fund from external grants and aids. Therefore, 20 TWh should be funded by the government and internal financial agencies if the country decides to stick to its greening commitment. By 2030, Bangladesh is expected to have the capacity to fund itself as its economic capacity will grow accordingly.
   Whenever policymakers intend to use hard-earned local revenue to transition a massive system like the power sector, they must pursue a thorough feasibility study considering all envisioned outcomes and limitations. A country must de-risk its investment to the maximum possible extent at its economic emergence and look for the lowest risk option in any financing decision. In that nexus, the following paragraph is crucial.
2) *Facilitating foreign direct investment:* Business scopes and launching processes should be widened and eased to attract foreign direct investment in the renewable power sector. It is crucial for Bangladesh as external investors will come up with the funds, experiences, and expertise in the renewable business. Therefore, motivating FDI inflow should be prioritised over allocating more government budget in the case of Bangladesh. However, many issues must be addressed to make the country a lucrative destination for external investors regarding renewable power generation and supply. The investment procedure, policy and mechanism should be free from hassle, bureaucratic procrastination and illicit practices. Suppose a foreign farm wants to do solar power business in Bangladesh. The proposed business mode may be ‘independent power production’ (IPP) and selling that power to the government by feeding it into the main grid. Sufficient land or rooftop spaces are required to install solar modules at a large scale. The allotment of space may require prioritisation, incentivisation and easement. For example, the investor may feel repelled if the land is too expensive to buy and install the plant. The offer will attract the traders if the government can lease out lands or allot public land at a cheaper rate. In Bangladesh, several bar-like landmasses form on the rivers due to siltation. The government may promptly allot these infertile and unproductive lands to foreign investors for farming power. The smoothening of such processes would make the ventures more feasible than when investors have to buy expensive cultivable lands.
   The government can formulate pertinent public policy to support renewable expansion and must endorse and enact these facilities in favour of interested investors. The country must protect their investment and the installations also. For example, the government may declare such plants as ‘’Key Point Installation’’ or KPI and deploy special protection or security forces to ensure their security.
   Buying electricity from large-scale solar plants in terms of bulk energy (MWh) through net metering instead of power (MW) may be another worthwhile policy incentivisation from the government as the latter often results in less profit. Tariff incentivisation for green power can be another attracter

to the business. The incentivisation fund may be collected from the carbon-emitting power producers. These forms of support may propel the inflow of foreign direct investment in the power sector of Bangladesh.

3) *Quality assurance of the renewable power systems:* Many sources of information confirm that there are often complaints against the quality of renewable systems in Bangladesh. Compromising with the quality harms the renewable transition in many ways. Some studies found serious non-conformity in Bangladesh's systems' longevity and efficiency (AL-Rasheedi *et al.*, 2020). Certain manufacturers, including REC, Panasonic, and SunPower, provide 25-year warranties with 90 per cent or greater residual power output. Bangladesh must consider estimating the total benefits from the plants throughout their lifespan.
   For calculating Return On Investment (ROI) and cost-benefit ratio, performance and degradation rates over the panel's lifetime must be considered (Thadani and Go, 2021). Cheaper solar panels will incur lower up-front costs and may perform well for many years. However, over time, most premium panels will experience less degradation, have a lower risk of malfunction, and continue to operate closer to their rated power rating, leading to increased electricity yields and higher returns. In 10 to 15 years, premium-quality panels with N-type cells will likely surpass low-quality panels by up to 10 per cent, which is significant considering feasible power production in the Bangladeshi context (IFC, 2015).

7.2.12 Addressing land scarcity

A widespread transition towards renewable power systems requires bulk generation schemes, and in Bangladesh, large-scale solar power plants are the proven solution to address this. Unfortunately, with an enormous population on a tiny piece of land, it can hardly afford space for accommodating large-scale solar plants. Bangladesh is still predominantly an agricultural economy. It must ensure food security for its people, maximising its agroproduction from its fertile lands. Farming solar power on its expensive and scarce lands is still less feasible than farming crops.

Moreover, food scarcity can beget severe sociopolitical troubles in the regions. Therefore, Bangladeshi policymakers generally consider using croplands as a low-priority, unattractive option. However, few mega solar plants have been erected in the infertile bar or salinated coastal regions where cultivation is not feasible. Several studies have already been conducted on how scarce land can be optimally used to harness solar power. Some of the significant findings are listed below, along with some new directions:

- The policymakers and stakeholders must first use the other spaces besides croplands. According to the 'National Solar Energy Roadmap 2021-41 prepared under the supervision of the Sustainable and Renewable Energy Development Authority (SREDA) and UNDP, Bangladesh can generate 20,000 megawatts of green electricity by 2041 with a medium-scale strategy of solar electrification despite the scarcity of land. On the other hand, this capacity can reach 30,000 megawatts in a high-level solar model with 5 per cent of river basin development land, industrial rooftops and other unused lands. For example, the rooftops of industrial buildings can provide substantial power if solar modules are installed on them (Talut, Bahaj and James, 2022). Due to rapid industrialisation, the scopes will be more comprehensive, generating more power.
- To increase the storage capacity of solar energy, cost-effective local battery production and import, and high-quality and cost-effective solar panels, converters, and DC components are required. In the future, medium and large-scale electricity storage (such as Tesla Storage South-Australia) should also be considered. Lithium-ion batteries are not the only solar-storage option; there are flow batteries, ion-salt-water batteries, gravity storage, etc. There are also electrolysis-based hydrogen storage and transport options.
- Government-affiliated Power distribution agencies like Desa-Desco-Palli Vidyut will have to permit to sell solar power and provide infrastructure services; in return, they will receive a commission. Individuals will store the solar power generated by their investment and sell the excess power. For this, the distribution system needs to be made smart. In remote and island areas, there is a need to

prioritize and encourage renewable solar and wind power generation instead of taking electricity from transmission projects. A community grid suitable for selling electricity generated by private investment is needed. There is a need for a bank-loan model for small-medium solar investment and to make battery recycling systems environment-friendly. As green electricity increases, demand for oil and gas will decrease, and dollar savings will increase. Land scarcity in Bangladesh suggests that there will be a requirement for massive deployment of urban and rural 'solar homes' with quality storage.

- Bangladesh is the most riverine country in the world, where the mighty basin of four river systems flowing through the Bangladesh Plain drains an area of some 1.5 million square kilometres. It also has 2% of its plainland full of small and medium-sized waterbodies, including some large lowland lakes. The previous assessment carried out in this thesis estimated that 50,000 acres of land are required to install a solar capacity (20% efficient panels) of 100GWp, which would barely deliver 180TWh of electricity per annum. More land will be required by 2050 to meet the future demand of 400TWh. However, if Bangladesh uses a tiny portion of its vast waterbodies and installs floating solar, it may generate substantial green power without stressing the acquisition of croplands. However, it has massive technoeconomic implementation challenges, including water contamination from hazardous materials used in the modules.
- Few studies claimed floating solar could contaminate waterbodies and destroy biodiversity (R. Chowdhury *et al.*, 2020). The policymakers must emphasise the technical advancement of the systems and modules regarding economic and environmental sustainability. The country can demand its solar modules to be made of materials free from arsenic or lead from the manufacturing countries.

7.2.13 Addressing efficiency issue

Several research and development activities are ongoing worldwide to enhance renewable energy technology's economic and technical efficiency. The success in such endeavours is also remarkable in the last few decades (Wang *et al.*, 2019; AL-Rasheedi *et al.*, 2020; Llanos *et al.*, 2020; Rahman *et al.*, 2022). In the last decade, the solar modules used in Bangladesh saw a substantial leap from 9% in 2010 to 22% in 2022. By the end of 2030, experts predict that some novel solar modules may have more than 30% conversion efficiency commercially. In the past decade, metal halide perovskite photovoltaics has been a key focus of study, with the power conversion efficiency of single-junction perovskite solar cells increasing from 3.8% to 25.5% already (Wang *et al.*, 2021; Brinkmann *et al.*, 2022). The previous trends and experiences extrapolate that the efficiency and cost will be more favourable for both the users and investors. Bangladesh needs to sharply consider these probabilities in its renewable transition roadmap and incorporate them as per its sociotechnical capacity. On the verge of severe land scarcity, the efficient modules will give more power, which is extremely important.

Bangladesh must carefully consider a very important aspect of renewable power generation systems. For example, if it starts to install large solar power plants with a life of 20 years now, perhaps there will be much more efficient systems before their life ends. Suppose it installs a 50 MW solar plant on 250 acres of land now with a life expectancy of 20 years and 20% conversion efficiency. However, a new solar module emerges within the next ten years with 30% efficiency even longer life and cheaper cost as the costs are falling rapidly. Then, the same area of land would produce less power throughout the lifespan of the plant whereas more power is already available ensuring better feasibility. Here, the government or the policymakers can make a requirement of the modules of 20-22% now with 10 years of lifespan so that after ten years the system can be replaced with better performing and more feasible ones. However, the calculation and forecast of the entire planning must be endorsed by expert analysts.

7.2.13.1 Nexus between Land Availability and Solar Efficiency

The model simulation depicted a profound impact of land availability on the probable transition capacity of Bangladesh (Figure 47). Bangladesh has already decided to book some of the lands for implementing its future solar aspirations. There are around 500 subdistricts in Bangladesh which is an essential administrative tier. The policymakers plan to acquire a few lands and install solar plants with more than 50MWp for each. However, the desired khasland (government-owned land) was unavailable everywhere. To resolve it, the government may purchase land at each subdistrict. Even if a minimal amount of land can be booked, acquired, or purchased now, the *future escalation of the technical efficiency of renewable power systems* will provide more power than it currently can.

Following the decision to prefer solar over other renewables, the next question arises about selecting the green power system or policy preference mode. Some key facts and points to consider regarding these issues are discussed here.

- Battery-equipped solar home systems have been proven successful in introducing modern energy access to the poverty-ridden rural people of Bangladesh (Samad *et al.*, 2013b). It had a wide array of positive multiplier effects on the socioeconomic state of the users too. However, the LCoE of the power produced from such tiny systems is far more than that of fossil-fueled systems. A study found that a 20W solar module coupled with a 12V deep-cycle lead-acid battery has a payback period of 26 years, whereas the product's lifespan is less than 20 years (Samad *et al.*, 2013b). The rapid penetration of new appliances like refrigerators, irons, television, etc., increased energy demand and subsequent consumption. Tiny rooftop solar home systems cannot supply adequate power to run these devices. In the meantime, the government has enhanced the total generation and diffused transmission across the country's primary grid, making those tiny systems almost obsolete. Nonetheless, the impassable regions and islands may still have such systems to retain modern energy access until the grid connection becomes viable. Upon considering this observation, the government should emphasise techno-economically sustainable policies targeting large-scale green power plants to generate bulk electricity and directly feed into the local grid.
- Since the land price is high and overpopulated, Bangladesh is still concerned about producing food for its people, and farming solar power on the croplands is still not viable. It needs to emphasise searching for other options, like using the large rooftops of manufacturing factories. An extensive study by the author found that more than 7000 MWp of solar generation capacity can be achieved by installing solar on that kind of premises (Talut, Bahaj and James, 2022). Therefore, the policymakers should eye on such ventures first that would provide cheaper green energy solutions saving expensive lands.
- Floating solar may also be an effective solution to destress the land requirement for solar plants. Though a recent study by JICA (Japan International Cooperation Agency) declared that installing solar modules may contaminate the water of the waterbodies of Bangladesh, damaging its biodiversity and ecosystem, the country can prioritise importing and installing panels free from hazardous materials. The inland waterbodies can be used for installing floating solar to generate power and reduce water evaporation. The saved water can also be used during the dry season through a solar pumping system to irrigate the lands.
- Applying net energy (MWh) metering instead of net power (MW) metering should be preferred and permitted. In the case of power metering, the government agrees and buys power at a minimum MW ceiling, discarding all the power produced below that ceiling. Since the scheme allows producers to use or sell the entire extracted energy, the payback period is lessened, and the business becomes more profitable. If net energy metering schemes are approved and enacted for large-scale solar plants, the investors will be motivated to a greater extent.
- Efficient and well-planned demand-side management can solve the issue of the 'generation-distribution' disparity. It increases the payback period making the business less attractive and profitable. Hence, the government should ease the green power sale from such schemes. However, it needs massive system enhancement if the intermittency of solar is considered across the national grid when the method is deployed nationwide.

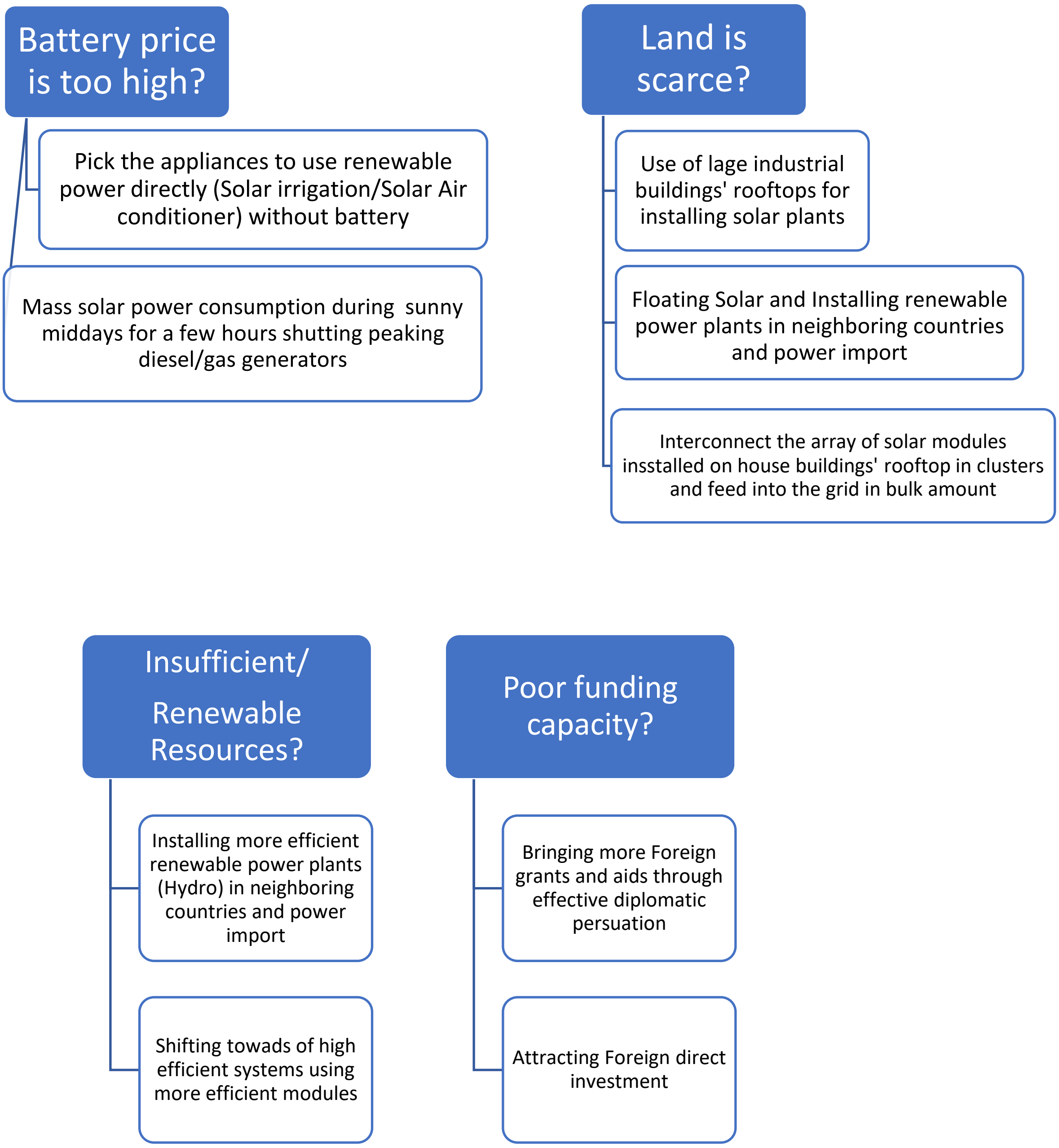


Figure 70: Examples of policy dilemma and determination of subsequent solutions

- Nevertheless, the government has already initiated the implementation of smart grid technologies like "Supervisory control and data acquisition" (SCADA) that can reduce the problem (Power Division, 2020). The weather forecast and solar irradiance mapping have improved over the past decades across the globe, and they can assist in designing precise supply management routines now. For example, Bangladesh could harness 2000 MWp from solar plants for two hours around noon pausing the operation of 1600 MW (assuming a performance ratio of 0.8) of diesel peaking power plants. It would save ample foreign currency sustainably and increase energy security as Bangladesh has to export diesel abroad. However, to extend the exploitation period from such green power plants smart grid system is mandatory. Optimistically, the policymakers have already taken action to make the grid smart by 2030. Nonetheless, the country should not miss the current opportunities to harness viable renewable power from its resources at its existing setup and according to its available capacity.
- Bangladesh needs to search for feasible areas of application where solar power can be directly used without adding expensive energy storage. **Solar irrigation pumps without batteries** can be an

excellent choice to make the take-off on the green transition pathway ensuring economic and environmental sustainability. Bangladesh remains predominantly an agronomic state, with agriculture contributing the most to employment, accounting for 12.5% of Bangladesh's GDP in 2020 and employing 42.7% of the total national workforce. Agriculture will continue to play a crucial role in the national economy to ensure the food security of a population of 180 million over the next two decades. Due to cyclical water level depletion, overharvesting, and a long dry season, irrigation by electrical and IC engine-driven pumps is an absolute necessity in Bangladesh, where year-round production of various crops has been a remarkable achievement. Bangladesh annually consumes 124,000 MT of diesel (IC engine pumps) and $3X10^6$ MWh of fossil-fuelled electricity (electric pumps) to power irrigation pumps (Islam, 2022).

- Bangladesh has already initiated attempts to install and utilise *solar irrigation pumps* countrywide to address carbon reduction in the context of escalating green electricity targets. It has already seen some success (Chandel, Naik and Chandel, 2017). An article by the author of the thesis explored and evaluated the likelihood and practicability of replacing all diesel and electrical irrigation pumps in Bangladesh with solar pumps (Islam, 2022). This study concluded that solar irrigation is viable for a subset of crops but not all, based on a systematic review of previously published papers and a few estimates, including recent technological improvements. The findings are encouraging because it is still possible to irrigate various other crops, thereby meeting 4% of Bangladesh's current electricity needs in an environmentally sensible manner. If this requirement is met instead of with diesel-powered and grid-powered pumps, and solar irrigation, it would cut carbon emissions by 2106 metric tons. It can significantly support Bangladesh in attaining its clean energy goals. The complete replacement is impractical because the required water pumping depths, compounded by the falling water table levels, threaten economic and technical viability. However, since the DC solar pump can be used directly without batteries, it is among the most feasible options with the shortest payback period.
- Policymakers and energy traders can pick the golden moment to start adding energy storage to the power systems as the price of such systems is falling rapidly (Davison *et al.*, 2018). Nevertheless, Bangladesh must consider using energy storage like batteries, capacitors or pumped hydro when the power price from such combined systems becomes competitive with fossil-fuelled systems. It must do so because baseload supply from erratic green resources cannot be accomplished without energy storage.
- Bangladesh's main challenges in harnessing wind electricity are poor wind velocity and sudden powerful gusts during cyclones. Poor wind speed reduces profitability by generating a negligible amount of power throughout the lifespan of the wind turbines. The policymakers and other stakeholders can adopt wind power technologies similarly when the offshore wind becomes cheaper or a novel technology offers a more feasible price. Though the turbine price fell drastically in terms of LCoE in the last two decades, it is still not bankable in Bangladesh for the above reasons. However, it may be feasible in the future, and Bangladesh should wait till then to consider bulk generation.

7.2.14 Adoption of Energy Storage Systems at a mass scale

A sufficient energy storage capacity is mandatory for a 100% green electricity sector predominately powered by intermittent resources like wind or solar to meet the baseload. Even in the evolving smart grid, some level of energy storage will be a key requirement. Stand-alone solar electricity is already proven to be an economically feasible green power generation option in terms of aggregated harvested energy. Unfortunately, a large-scale solar power plant with mass energy storage like batteries is still higher in LCoE than fossil-fuelled plants. Other energy storage options like pumped hydro are not geopolitically feasible in Bangladesh. However, the prices of modules and batteries are rapidly decreasing simultaneously due to technical advancement. The projection forecast of such items denotes that baseload-supplying battery-added solar plants may become cheaper than coal power by 2030 (Deorah *et al.*, 2020). Battery pack price forecasts are becoming more accurate as global Li-ion battery production rises in response to escalated EV demand (Turksoy, Teke and Alkaya, 2020).

Capital expenditure has also been reduced substantially in the case of solar with battery storage. Regarding power generation installed capacity capital costs, PV with storage stands at US$1748/kW (for a 150 MWp Plant), and coal stands at US$ 4074 (For a 650 MW plant) (US Energy Information Administration, 2022). However, a coal-fired plant still holds superiority in delivering reliable power for longer periods. Moreover, sometimes in Bangladesh, heavy rainfall sets in for weeks, reducing solar irradiance, which may result in the batteries getting discharged, disrupting the baseload capacity. Therefore, policymakers must keep the monsoon in mind when solar energy is inconsistent and cannot be a reliable resource for ensuring baseload. Before a more reliable system emerges through technical advancement, they may consider keeping some fossil-fuelled generation in the energy mix to avoid blackouts.

The neighbouring country, India, has long had a similar track record to Bangladesh in terms of pricing electricity. A study on the Indian context predicted that the capital costs for deep-cycle Li-ion batteries co-located with storage projects in India would fall to US$92/kWh in 2030 from US$187/kWh in 2020 (Deorah *et al.*, 2020). The levelized cost of storage (LCoS) of a standalone BESS (battery energy storage system) is estimated to be ~$0.095/kWh by 2020, ~$0.07/kWh by 2025, and ~$0.06/kWh by 2030. In contrast, by 2030, coal power will have a larger LCoE, even excluding the highly probable carbon tax. A similar prediction can be applied in the Bangladeshi context. Therefore, 2030 will be the transition period to deploy BESS at a large scale to ensure baseload supply in Bangladesh.

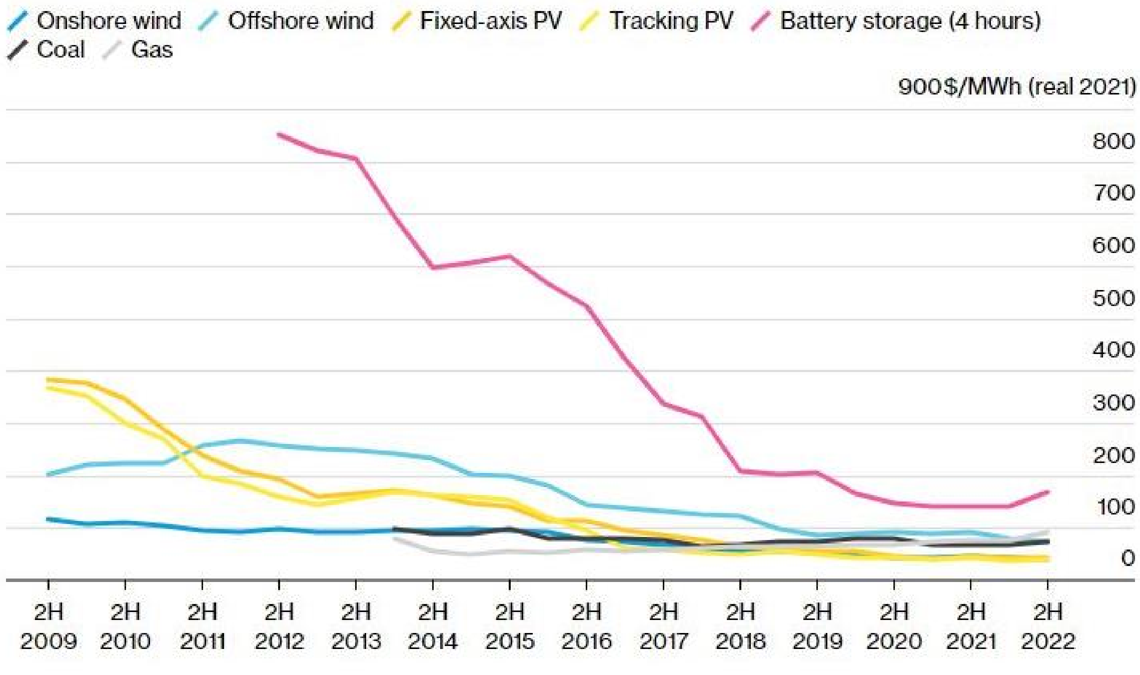


Figure 71 Global levelised cost of electricity benchmark (Source: BloombergNEF,2023)

The economic case for RE (particularly PV) and storage systems is strong. Low RE prices and low battery storage costs may cause disruptions in Bangladesh's attempts to fulfil its rising energy demands from coal. Solar plants also have substantially shorter planning and development timelines (1–1.5 years as opposed to 4-6 years) than traditional thermal power plants. Therefore, installing RE and storage systems could significantly reduce the risk of the energy supply falling short or exceeding the energy demand in a dynamic economy.

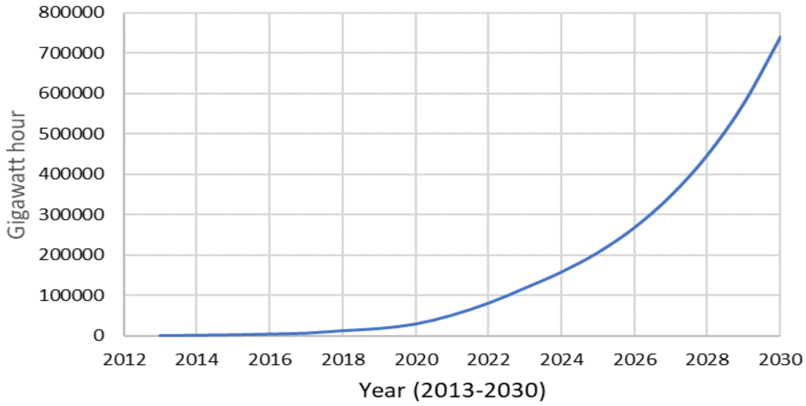


Figure 72 Projected cumulative deployment capacity of the energy storage market worldwide from 2013 to 2020, with forecast figures up to 2030 (in gigawatt hours)[47]

Additionally, despite the possibility of continued annual coal price increases, these costs are generally conjectured to be inflation-proof. The cost differential between PV-plus-storage assets and thermal assets is anticipated to widen in the future. As a result, making new investments in thermal power plants with 25–30-year lifespans could be extremely risky financially for any country. Coal is not available in Bangladesh to any significant extent either. Therefore, solar plants with batteries will likely become a very attractive option for energy traders due to less operational cost.

However, coherent policy and regulatory efforts are required to increase simultaneous renewable power and storage deployment in Bangladesh at feasible prices. These efforts could include a clear policy direction to increase domestic battery production through guaranteed demand and a road map for skill development and job creation.

A study investigates Germany's PV surplus generation and storage requirements (Schill, Zerrahn and Kunz, 2017). Excess energies are generally found to be low, but there are peaks of high surplus power. It is stated that further research is required to answer some concerns, including the optimal combination of storage, curtailment, and other flexibility options. Investigating the interaction between various energy storage technologies and network expansion, power-to-heat, and thermal facilities appears to be a fruitful study area. Additionally, the complete system value of storage technologies, including their capacity value and the provision of ancillary services, should be investigated.

This analysis focuses solely on the economic case for battery storage systems. It does not investigate the technical and operational viability of replacing new investments in coal with PV plus storage. Such factors necessitate a comprehensive analysis of grid dispatch, which is the focus of our ongoing and prospective work. The integration of grid-scale battery storage into Bangladesh's resource planning over the next decade and the attendant effects on electric system costs must be studied. The economic analysis presented here could facilitate a cost-benefit analysis for Bangladesh's capacity expansion and investment decisions.

[47] Cumulative global energy storage deployment 2013-2030, Published by Bruna Alves, Feb 17, 2023, Colected from Statista (https://www.statista.com/statistics/728652/projected-energy-storage-market-capacity-deployment-globally/)

8 Key Research Findings

The study sought and observed the rationales for transitioning Bangladesh's electricity sector towards renewable (See section 2). Renewable electricity is expected to be cheaper than fossil-fueled power. It was found to be a strong reason. Worldwide concerns related to global warming, the severe vulnerability of Bangladesh to climate change, and compulsion from various pressure groups are also the causes. However, technoeconomic feasibility considering reliability and security was found to be the primary challenge at present (See sections 5.1.4, 5.1.8, 5.1.6). It explored the current state and capacity of Bangladesh for such a challenge. Several government organisations are already deployed in formulating, enacting, and implementing energy exploration, extraction, and power generation policies. However, the organisational capacities are limited by their inefficiency, unskilled workforce, and some undesired malpractices (See 2.5). Moreover, the technoeconomic capacities for local manufacturing of renewable systems and accessories are also inadequate, and the sector is almost entirely dependent upon imported items. Research and development activities for such a changeover are also underfinanced due to poor affordability (See section 6.2.1).

The study initially estimated Bangladesh's future power demand through a regression and extrapolation model, considering population growth, economic development, seasonal variability, and transport decarbonisation. It found that by 2041 (The projected year of graduating to a developed country), the energy demand may rise to a saturation point of 400-500 TWh mainly due to the cooling load and EV use increase (See section 4.1). The study explored the renewable electricity generation potential of Bangladesh from different resources. Solar was found to be the most potent and feasible to exploit. Through reviewing a few past studies and new estimations, it was found that around 200 GWp of solar can be achieved using the coastal fallow lands, bar lands and the rooftops of large buildings (See section 7.1.2). It would generate only 58 TWh of electricity at a module efficiency of 20%. Moreover, the agronomic state is still struggling to ensure its food security and to maximise the use of every type of land for growing food. Therefore, it is not pragmatic for Bangladesh to ensure 100% green power from its own land resources. Based on the current scenario, it has to depend on the future escalation in the efficiency of such systems and green power imports from neighbouring countries to make it happen.

The study has also highlighted a complex nexus between land availability and solar power generation. The area with the highest insolation is enriched with hilly flora and fauna. More than 125,000 acres of land would be required (See section 5.1) to generate the projected needed electricity of 400-500 TWh by 2040, which is tremendously difficult to avail. The requirement may amplify more to facilitate the baseload supply and consistent flow of green electricity throughout the year. However, later investigations revealed optimism based on future renewable and storage system's technical advancements (See section 5.1.4, 5.1.10).

There are opportunities to increase land availability due to the salination of the coastal belt area of Bangladesh, as saline intrusion makes lands infertile and challenging to produce crops. Floating solar can also be effective as hundreds of rivers and waterbodies heavily crisscrossed the country. The policymakers are considering the feasibility of establishing floating solar projects on lakes and barren sedimented river bars in Bangladesh. This is in response to the country's land shortage issues, which pose challenges for the implementation of large-scale solar schemes. However, it is important to note that the ecosystems in these locations may be susceptible to 174mpeding174zatio issues, which necessitate additional research and analysis. The model incorporated a 'land availability' variable with a logistic trendline and the simulation showed that if the rate of availing lands for installing solar remains sufficient, the transition may be possible by 2060. However, it must be supported by many other variables' positive influence (Figure 47). he research endeavoured to address several questions about finding the optimum timely policy actions for transitioning Bangladesh to renewable power at its fullest conceivable extent. Then it determined the magnitude, aspects, and prospects of available renewable energy resources in Bangladesh by mapping the resources: solar, wind, tidal, biomass etc (See section 2.6). The results underpinned sufficient prospects at the expense of valuable agro and forest lands the country cannot afford to compromise with. The study estimated and analysed the renewable potential and capacity to meet the country's future demand. Though by the term 'power', the study emphasised electricity, it comprehended that issues like decarbonisation of transport by promoting electric vehicles or cooking by electric cookstoves would directly increase the electricity demand. That is why the study considered them substantial parts of the study.

The backbone of this doctoral research was the sociotechnical capacity modelling for the capacity of Bangladesh to transform its fossil-fuel-based power sector to that derived from renewable energy. The study endorsed its needs and novelty through many rationalisations, allowing its entry into the existing knowledge pool. It is original considering many dimensions of contextualisation and modelling approach. The main reason for conducting the modelling and simulation was to challenge the business-as-usual perception of the major decision-makers. Most believed the Bangladeshi economy could not afford a massive renewable transition now due to intermittency and feasibility issues. The research incorporated green power transition capacity modelling to optimise economic growth/purchasing power, price changes, etc. It considered the rise in affordability, the efficiency of renewable technology, changes in prices of fossil fuel and renewable power and other factors in future with time. It gave the idea of quantifying the sociotechnical capacity of Bangladesh to accelerate its renewable transition based on several variables' previous and future trends (2.11.1.12). It mathematically determined how and to what extent the variables influence the transition in the Bangladeshi context. It used multiple boundary conditions and constraints based on several socioeconomic and sociotechnical features of Bangladesh and the wider world. Following the findings, the study identified the main challenges and obstacles towards the target of nearly 100% renewable power in future and to determine how and at what rate the share of renewable energy in the entire energy mix should be augmented over time. The simulations exhibit that by 2030, Bangladesh has little chance to move towards massive transition in its power sector. However, after 2030, when the generation module and the energy storage price will be cheaper, the transition may rise exponentially if appropriate policies are adopted and enacted (5.1.1).

The systematic literature review on the transition modelling based on socioeconomic parameters for Bangladesh identified the research gap and endorsed the rationale for the research. In the prior work, the renewable energy potential of Bangladesh denoted that it would be challenging for Bangladesh to meet the entire demand with green power. Based on the findings, this work suggested how the renewable share in the energy mix should be progressively elevated according to factors like the future escalation in financial affordability, land availability or the technical advancement of the suitable renewable systems' overall efficiency and other factors for the country. The outcomes will also suggest the priority sectors be ranked according to their level of influence. The common difficulty of' no singular solution' occurred in this socioeconomic/technoeconomic capacity modelling case for the incumbent study. The solution produced by MATLAB's generic nonlinear equations solver package gives multiple value sets of coefficients k for different iterations (2.11.1.13). The research used a few logical and plausible reasonings pertinent to the Bangladeshi context to determine the most rational set—the multiple nonlinear regression produced different weighting for the variables with different iterations. Many sets of 'k' values (model coefficients) were produced through iterations using different boundary conditions based on rational predictions to address the issue. Some examples are the price of the energy storage system will never go negative or the cumulative amount of foreign grants will not go beyond five billion US dollars, followed by predictions from the Ministry of Finance and several pieces of literature. After achieving a comparatively rational set, simulation was carried out by varying the values of the variables. A set was discarded if anything unpragmatic was produced in the forecast (e.g., Bangladesh will have the capacity to reach 100% green power within the next five years). This way, after several iterations, the best rationally conforming set of values of 'k' was taken for fitting the model (10.3.4).

Hitherto, the simulation results indicate the priorities should be ranked as follows: foreign aid> energy storage price> system efficiency>direct green power import>carbon taxation>per capita income>renewable power budget>land acquisition of large solar plant>renewable electricity price in case of Bangladesh. The order may be susceptible to additional adjustments based on future mutations in transition and the extent of their connections. The model has the readjusting capacity to address the individual changes in the variables. This work used a novel technique to simulate the fundamental drivers of the green power transition in a developing nation like Bangladesh. The sustainable transition is mostly supply-driven and government-led. Nevertheless, the model used only 10-years data for vector autoregression, which may be modified anytime for longer durations. The next tasks focused on the green awareness survey and interviews. The extracts endorsed the consistency between the modelled findings and the intents of the involved stakeholders. The findings showed that the stakeholders are not optimistic about achieving a 100% renewable Bangladesh before 2080-90. However, considering several plausible weighted projections and existing examples, the model suggests it is possible by 2050-2060. By 2050, the lion's share of electricity can be generated from renewable resources in Bangladesh if the transition is adopted by the policymakers.

Subsequently, it explored the different policy ideas and options regarding the transformation, considering the existing trends in transition. It analysed each policy and its implications for Bangladesh's implementable renewable pathway through comparative evaluation. The study stressed the responses from several entities through surveys and interviews. The incumbent policymakers and other functioning stakeholders gave views on several issues like land scarcity, unaffordability, system inefficiency, and lack of technical capacity and experience. Their responses, on an average, implied a pessimist prediction about the 100% transition which may not be possible before 2090-2100 (3.1.1).

The study optimised the significant policy decisions from the government regarding future energy aspiration through comparative analyses through sensible substitutions (**Error! Reference source not found.**). For e xample, when the study found that land scarcity is impeding the growth of solar power at a large scale, it looked for the scope to install solar plants on large industrial buildings' rooftops and estimated that they can deliver 7500 MWp of solar capacity without stressing expensive land. When economic affordability was questioned, the study emphasised bringing more foreign support and investment to increase renewable share (7.1.2). It also recommended not using expensive energy storage initially to retain the feasibility of selecting application options where batteries may not be required. The study suggested that when the economy becomes more robust and well-off, it can consider purchasing bulk storage systems to ensure base load supply from renewable. Direct solar irrigation through a DC irrigation pump or net energy metering schemes is an appropriate choice to keep the bankability of the renewable transition at a satisfactory rate at the current stage (Nexus between Land Availability and Solar Efficiency). Meanwhile, renewable systems' economic and technical efficiency will also increase in their feasibility.

Estimations show, that by transitioning from diesel gensets to solar photovoltaic (PV) systems and other renewable sources such as biogas, the dairy cooling sector has the potential to mitigate around 12,000 tons of carbon dioxide (CO_2) emissions per year by 2030 (7.1.4). The model simulation found that energy storage systems (ESS) will be essential when a baseload supply is needed from renewables. In the case of Bangladesh, this study predicted that by 2030, it should initiate mass deployment of battery storage to save energy for dusk time baseload supply (5.1.10). However, even before 2030, it can gradually raise its battery storage capacity, and then after 2030, it can speed up to exploit the optimum economic benefits. The rampant fall in ESS price is expected to have the capacity to replace fossil-fueled power systems entirely by 2050 (Figure 51). The impact of subsidisation or incentivisation on renewable power systems may have a crucial impact on the electricity sector of Bangladesh. Abrupt subsidisation at a wide scale can disrupt fossil-fuelled baseload power production by independent power producers (IPPs). This may happen once they find out renewable feed-in tariff is more profitable than the business running on fossil fuel. Unfortunately, the subsidisation or incentivisation schemes are still not very lucrative for the IPPs and coal is still more profitable for the investors. Therefore, the government must be very careful in setting up the optimum level of subsidisation for such schemes, which would not disrupt the consistent baseload supply. It can be maintained by channeling the subsidisation towards renewable power generation with a sufficient energy storage system. The optimisation can be conducted by calculating the desired replacement rate of the fossil-fuelled system by the reliable renewable system. Nevertheless, the desired outcome of the subsidisation or incentivisation must be carefully followed up, and carbon taxation on the fossil-fuelled systems can be applied accordingly (Figure 43, Figure 72).

The study put substantial emphasis on determining the roles, responsibilities, and interests of the first world and the neighbouring countries in the transition of Bangladesh, assessing the need for effective climate/energy diplomacy to achieve the aid (See Sections 5.1.5, 5.1.8 and 7.2). It included a study on the prospects of power import and constructing a regional power grid across the SAARC states that may meet all the region's demands from its green resources at a much cheaper rate (See section 7.2). It included evidence to show how the interconnected renewable power hubs can reduce the spatiotemporal variability of the intermittent supply of renewable electricity, making it more feasible by paring down the need for expensive storage. However, very effective diplomatic approaches are required to realise such a mega-venture.

Recent geopolitical upheaval and cataclysmic events, such as the pandemic, have pushed the energy sector in directions the globe has not seen in a very long time. Conventional power generation swiftly replaced safer and greener technology in industrialised nations. The developing nations continue to struggle to provide their populace with even the smallest quantity of modern energy. Bangladesh, with a population of 180 million, is one of the lowest energy consumers, using only 614 kWh per person, and still struggles to provide minimal energy for everyone to lead a civic life. Bangladesh was planning its energy policy strategies around the coal-fired power generation technology for its economic benefits, despite the adverse effects of harvesting energy from GHG-emitting sources. Coal-fired power generation is still less expensive and more reliable than currently available renewable energy sources. However, in 2023, it revoked the plan for installing ten coal fired plants due to sudden surge in the fuel price and global pressure from environmental groups. Over the next two decades, renewable energy sources will likely decrease consumer prices by around 10% per year and become more economically feasible than polluting sources. Bangladesh must wait until renewable energy is financially feasible due to a lack of financial affordability and reliable resources. To absorb the transition shock after two decades, officials must adopt at least a "go-slow" strategy in preparing the energy industry for the unplanned shift.

Estimating the social cost of conventional sources is targeted to be compensated by replacing conventional sources with renewable ones. After using different mathematical models, the preliminary renewable energy policy was made to drive the future transition by only 15% in the energy mix by the next 15 years, not more. After that, in 2020, the country vowed to increase the transformation rate. The country could not yet make 100% electricity coverage, let alone massive electrification for a civilised lifestyle. It concentrates on the optimised and the most effective energy plan to minimize the effect on the environment, whilst maturing economic growth on the way. At this juncture, the consideration of the social cost of GHG emission may be included and used for the development of a mathematical relationship for the policy directives. The policymakers are also considering what portion of total power can be produced from renewable sources without hindering the expected economic growth. Consideration of the optimal economic efficiency of power generation comes up at this point. There should be a time-bound progressive plan for funding renewables to replace conventional sources. Since affordability will increase with economic growth, a plan can be made. Considering all the forecasts, the rapid and massive transition goals may be activated after 2030 for Bangladesh (Figure 41). Nonetheless, if something revolutionary is innovated in green technology in the meantime, there may be a rapid paradigm shift (Figure 44).

For energy transition in developing countries, colossal finance is the biggest challenge at the scale of trillions of dollars. For example, a partial transition to a renewable world by 2035 requires a fund of more than 53 trillion dollars, even much more than the current global GDP (Hall, et al., 2015). Complete infrastructural transition in large technoeconomic systems has taken six to seven decades in the past (Grübler, 2016). However, the pace is accelerated due to faster technological diffusivity. In addition, new financial strategies are needed to align the financial schemes with the actual physical demands for long-term sustainable investment regarding transition (Grubb, et al., 2014). Addressing multiple sociotechnical factors simultaneously is undoubtedly an uphill task for a developing country.

The study reveals that the most crucial support is the transition finance for developing countries and it should come from developed countries (5.1.5). Since most of the developing countries are still considering the installation of conventional GHG emitting plants due to cheaper LcoE, developing states can regress it significantly by financing those states to push them forward towards renewable technology. In Bangladesh, there are already some efforts from the World Bank and the 'Renewable Energy and Energy efficiency program' commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) which helped to install more than four million small solar home systems in rural, remote places where electricity from the national grid is not economically viable (BMZ, 2014). Though it introduced modern electricity to the poor people for lighting and light entertainment like television, the amount of energy is still essentially trivial. It cannot contribute significantly to the growth of the economy. Nevertheless, this is an impressive step to energise regions where people cannot afford it from the national grid. They are also assisting Bangladesh in adopting energy-efficient furnaces and bio-gas plants in those underprivileged premises (7.1.6).

The country is in dire need of enhancing its capacity to manufacture, maintain and operate the technology of renewables. There should be plants inside the country where wind turbines or solar PV cells can be produced locally. Foreign Direct Investors should heed this because, with a large population of 170 million, it is a big market for such a commodity. Likewise, consuming more electricity will open doors for other trades and services (Section 3). Hi-tech innovation research in transition is not affordable yet for a developing country like Bangladesh, particularly in the energy arena. At the same time, developed states can make rigorous efforts due to their superior technoeconomic capacity. Nonetheless, it is trying to fund innovative initiatives and design the innovation framework for sustainable development. A Sustainable and Renewable Energy Development Authority was founded to promote sustainable energy and to build an energy-conscious nation to ensure energy security and to reduce carbon emissions under the legal obligation of several different Acts and policies in favour of greening the development process (SREDA, 2014). The government created a separate governance innovation unit, emphasising local innovation efforts. Many educational institutions have funds for sustainable energy studies and research from local and international agencies. The Institute of Energy housed in the country's apex university (Dhaka University) is making efforts to study renewable potentials, prospects of local innovations and the efficiency of various technologies to derive the most appropriate systems for Bangladesh. To attain the goals of these initiatives, the Bangladesh government should follow the success stories worldwide and work with international energy experts and aid agencies.

At the primary stage for the preparation towards transition, local innovation should be emphasised and directed towards the enhancement of energy efficiency of the currently available devices. The practice of energy saving and monitoring and regulations for energy conservation must be effectively imposed and activated in the execution of action plans (7.2.13). Most developing nations pay little attention to the transition to sustainable energy systems owing to a lack of financial resources. Nonetheless, they are expected to be the most severely affected by global warming due to GHG emissions. In contrast, the industrialised world is already energy-saturated and transitioning. It is also expected that 2050 energy consumption will double due to the growth of the emerging globe. If traditional GHG-producing sources achieve this, the global temperature rise will surpass 2^0 Celsius above the pre-industrial era well before 2050. It will wreak devastation on humans, not just the low-lying sub-Saharan, South Pacific, and south-east Asian emerging nations. Bangladesh is projected to lose one-third of its land to the Indian Ocean, and more than fifty million people will be forced to flee their homes due to climate change. Climate change is a global problem that a single nation can never address; thus, Bangladesh's tremendous economic progress cannot be stifled by an overnight transition to expensive and unreliable renewable energy sources. In this predicament, the state must develop a comprehensive, realistic, and optimised Renewable Energy Strategy to address the difficulties from several angles.

The study reviewed various sources and assessed the contextual differences between the transitions in developed and developing countries. Due to their lack of financial, intellectual, and technological resources, emerging nations will likely formulate an energy strategy radically different from that of wealthy nations. Therefore, their transition policy must include development partners, associates and specialists in every formulation, adoption, and implementation step. Monitoring and evaluation since renewable technology are comparatively novel, innovations, operations, success stories, research, and other activities are now utterly based on the developed world. The cost-benefit analysis of the possible implications of the goals must be done from social context, economic, and environmental viewpoints (7.2.11). Enhancing the ability of central and local employees is also essential at every level, and this must be emphasised in the policy agenda. The strategy should concentrate on determining the most feasible pace of replacing conventional sources with renewable ones, taking into account primarily two criteria concurrently. The first is the growth required for balanced economic development, and the second is the environmental effect of emissions. Optimising between these two alternatives, the most feasible combination should be introduced and accelerated progressively by establishing logical checkpoints. The study has already implied at a few illustrative examples in it. The transition milestones should converge towards the moment of inflexion when the economic efficiency of renewables will exceed that of fossil fuels (**Error! Reference source not found.**). Numerous t rustworthy predictions regarding the techno-economic paradigm change in the energy arena may draw conclusions that specialists can determine and employ. Policymakers should emphasise the incentives (5.1.3) for entrepreneurs in renewable industries and foreign direct investment (5.1.5).

The study found that, as a result of the global dimension of climate change and its repercussions, Climate and Energy Diplomacy should be given significant weight in the policy framework (7.2,7.2.8,7.2.5). The policy must adopt a strategy of strongly persuading international organisations, forums, groups, agencies, and companies to make climate funds and other aids available and advocating vehemently for the modification of undesirable outcomes for which poverty-stricken nations are not responsible. The study presented that standard financial measures like subsidies and tax breaks may be essential to facilitate the transition to sustainable systems. Public-private collaboration and NGO engagement for the first launch of modest renewable initiatives have proven effective in Bangladesh. Four million micro solar home systems have been constructed in distant rural areas where transmission from the national grid is either impractical or temporarily feasible owing to impregnability. These sorts of provisions should be supported and facilitated by policy alternatives. In addition to these facts and elements, all conceivable parameters and variables should be enumerated, evaluated, and thoughtfully addressed while establishing the policy. Numerous actors, such as expanders or containers, including the Ministry of Energy and Environment, other executive bodies such as power development and distribution boards, environment groups, large, medium, and small entrepreneurs, civil society, foreign firms, consultants, etc., must be included during policymaking. Their respective management strategies must also be determined and reflected in the policy. The experts may include and use a variety of formulation approaches to discover the optimal optimisation of the policy variables. A legal framework that is sociable and accessible is essential for the effective execution of policies. Legal standards and regulatory requirements may be created via legislative procedures that can have a profoundly obligatory effect on the execution of the policy in a secure manner. The legislative framework may also permit the formation and activation of new agencies for the future execution of the policies (7.2.12,7.1.8,7.1.9.3).

Creating and accepting a renewable energy strategy for developing nations is compatible with both the incrementalism and limited rationality theories of policymaking. On such important matters, it is necessary to avoid bureaucratic inertia, which the optimistic outlook of the policymakers and other stakeholders makes simple. Bangladesh is still a young nation-state that has only lately become conscious of national principles and other democratic standards. The emergence of new oligarch interest groups is quite probable at this phase. They would overexploit commercial opportunities via various collusive techniques while attempting to maintain them for an extended time, severely compromising the entire system. Policymakers should take this problem seriously and include preventative measures based on logic, equality, and fairness in delivering and distributing the services into their policies. Preference among policy objectives and alternatives is an essential aspect of policy design. Bangladesh is a burgeoning economy of the lower middle class and an extremely energy-poor nation, economic progress dependent on power generation must be prioritised over environmental sustainability.

Politicians should evaluate the Political Stability of the policy with the utmost care and take the appropriate steps, such as awareness and widespread public participation, within the policy framework. This sort of policy's extensive and mass-participation techniques assures the policy's sustainability, even if the governing party changes after an election. The political viability of a renewable energy strategy for developing governments like Bangladesh requires a hybrid approach that combines top-down and bottom-up implementations since this enables the most significant engagement of mass populations in policy processes. In addition, the nation lacks the managerial and technical capabilities necessary for these new initiatives. Private businesses must improve these capabilities from a market pull standpoint to eliminate the possibility of government inefficiencies and delays.

Evaluating implementation capability is a fundamental need of the policy. It indicates the need for further capacity augmentation and assists in establishing the milestones for policy plan implementation. In addition, executive bodies' competence and likely inertia against any institutional change must be evaluated. Introduction and distribution on a large scale of a novel product, such as renewable devices, in a developing nation would require hiring new personnel and expanding the capabilities of other relevant organisations. The policymakers must consistently progress in implementation and capacity building as they reach and surpass successive milestones.

As a result of a variety of socioeconomic factors, the future of emerging nations is undoubtedly more unclear than that of affluent ones. During risk studies for the policy, these unanticipated complexities should be quantified if they form during policy implementation. Renewable sources are not nearly as dependable as conventional ones. Hence, these sources should first be deployed in less significant buildings. For example, rural schools or libraries should be given precedence over hospitals for installing renewable devices, as power loss in emergency circumstances might be life-threatening for the patients in a hospital.

Similarly, distant, isolated locations like islands should be selected over the rest, considering the viability and cost of individuals for transporting electricity from the national grid. Better developments and inventions in energy technology may facilitate a quick paradigm change within the energy system. To reduce the investment risk for a developing nation such as Bangladesh, policymakers should rigorously evaluate the system's longevity and life cycle. Initially, financial institutions must be concerned about just the micro-units of renewable energy sources to decrease the danger of failing to receive the cashback from investment. This model has already demonstrated success in Bangladesh as the six million micro-solar's aggregated generation was added to it. Gradually, they may enhance the credit disbursement, but only if the acceptable turnovers improve. Under the policy framework, the formation of promotional funds such as the green fund, climate change trust fund, and the recruitment of donors and development partners should be enhanced. The Bangladesh Bank cannot afford the risk of financial hacks to unknown destinations such as occurred in 2016. Hence success studies of commercial banks and other financial institutions are necessary. Tax, tariff, or duty exemptions on renewable energy items and associated services may be maximised to encourage importers and investors (5.1.5). The government should promote foreign companies with attractive tax incentives and infrastructure assistance, which should be included in the strategy.

Developing nations must conduct periodic policy assessments and monitoring to mitigate the risk of financial losses (5.1.3). Evaluations of renewable energy policies should be quantitatively and qualitatively multidimensional. There should be a resolute monitoring authority, and plans should be sustained, adjusted, or altered depending on their researched suggestions. The assessment may be based on parameters such as the durability of the devices, the rate of financial return, customer happiness, and demand growth, among others. For instance, if the producer's service life falls short of expectations, the suppliers may be held liable. This legislative measure may be added to the policy framework and adjusted based on the assessment committee'' response.

8.1 Original contributions of the Research

The study has produced the following original contributions to the knowledge pool:

i) A systematic literature review of the transition modelling converging towards the Bangladeshi context was conducted. The end focus was the sociotechnical capacity modelling for transitioning Bangladesh towards 100% renewable power. The review revealed that no such study was published before this research.

ii) A forecast model for deducing the future power demand in Bangladesh was constructed. It included seasonal periodicity, wide use of air-cooling devices, and EV use. It also incorporated a logistic function for rationalising the future saturation coupled with sinusoidal trends to adjust seasonal fluctuations. Previous studies did not exclusively consider those factors.

iii) A sociotechnical capacity model for determining the amount of maximum achievable renewable power within the affordable range of Bangladesh was introduced. Notable features include:

- Sociotechnical capacity modelling for transitioning the Bangladeshi power sector was not studied before. Therefore, it has a contextual novelty.
- It considered several variables that have endemic characteristics pertinent to the Bangladeshi context. Consideration of sociotechnical and socioeconomic variables like foreign aid, budgetary allotment, energy storage price, affordability, system efficiency, direct green power import, land availability, green power price, carbon taxation etc., in a single modelling approach was not found in past studies.
- A non-linear logistic curve was fitted to the ten-year data by vector autoregression (VAR) and extrapolated according to those variables' rationally approximated temporal loci. The individual trend prediction for each variable was not used in the past models.
- The model graphically analysed the sensitivity of each variable's impact by varying their values and modifying the boundary conditions. This analytical approach was not used in previous studies.
- The simulation gives the maximum achievable amount of renewable power generation capacity at different periods in the future. It demonstrated the plausible future pathways for achieving the maximum renewable generation influenced by the independent variables. It also showed the changes in the output while varying the input values, individually or all together. These features were not available in any of the past models.
- The influential variables were ranked according to their extent of influential capacity to accelerate or decelerate the transition. The model implied that foreign grants played the most vital role in making it happen to date. However, the flow of such grants or aids will be reduced with the local affordability rise. Therefore, the government must elevate its own budgetary allocation for green power generation. These suggestions extracted from the model simulation were not endorsed in past works.

iv) The findings suggest that foreign grants and supports are essential for Bangladesh to retain and escalate its renewable momentum which the previous studies did not stress.

v) The research produced numerous suggestions regarding steering the transition in the right direction at a maximum pace. It discussed several modes of solutions and feasible ways to speed up renewable generation corresponding to the Bangladeshi context. It hinted at the optimisation trajectories and selection techniques among the policy options while simultaneously taking care of the risks. For example, a land-scarce country must use the available options first where land is less required. Then it discussed such ideas as using rooftops of large industrial buildings under a net metering scheme or floating solar as Bangladesh is a highly riverine country full of water bodies. Many other such optimum policy recommendations were added to the work. Such consultative annexure is rare in past works following a transition model simulation's result.

8.2 Further research needs

By the year 2030, the global economy has the potential to realise annual savings of up to $4.2 trillion through the mitigation of pollution and climate-related consequences. Furthermore, the implementation of efficient and sustainable renewable technologies can contribute to the formation of a more robust system that is less susceptible to market fluctuations. This can enhance resilience and bolster energy security by expanding the range of available power supply alternatives. Energy transition study is important because it helps us understand the shift from traditional fossil fuel-based energy sources to renewable energy sources. This transition is necessary to reduce greenhouse gas emissions, mitigate climate change, and ensure a sustainable future for generations to come. The socioeconomic progression is versatile and wide-ranging among the developing states around the world. While the developed countries share several common aspects regarding transition, the influential variables are highly contextual in the case of developing regions across the globe. Therefore, capturing the renewable transition dynamics becomes difficult through the available approaches. While ``Transition Modelling`` is a popular tool for deciding to fit the available data on a suitable template, it is also challenging to select one due to the lack of extensive modelling studies among developing country contexts. Moreover, the renewable escalation is relatively a new event among these countries that did not lead the R&D in this domain. They got access to the technology predominately through free-riding by the developed states that pioneered this novel technology. Driven by market pull and demand push, cutting-edge inventions in the domain of green power technology took place in the R&D-rich countries. Research on system transition and the transition dynamics are also relatively carried out in larger numbers than in developed states whose contexts are significantly distinguishable. This research addressed many critical interconnected issues simultaneously. The intended outcomes can be improved by segregating them and conducting discrete research on each of them separately. Say for example, "the effect of foreign supports on transition pathways" can be a primary focus of extensive research. The "optimal financial mechanism for transition" can also be an important issue to be investigated for determining better policy recommendations. "Optimisation of land use for maximising solar power harvest" and "determining the optimum rate for carbon taxation" may be other research foci in the Bangladeshi context where both are found to play crucial roles in the transition.

The modelling was based on the data for only a decade which may be subjected to debates though sufficient rationales were presented in favour of it. The future is always uncertain and stochastic. However, to formulate visionary strategies for the development of the state, a policymaker must depend on the policy forecasts based on scientifically obtained findings. Mathematically or statistically modelled transition scenarios are highly regarded for obtaining such understanding for making optimum plans or programs. The research delivers the acumen for the policymakers and thinkers. However, before taking any policy action, the contemporary conditions are to be thoroughly investigated since the transition is highly dynamic in nature. It is highly sensitive to the contemporary stochasticity. For example, the Covid pandemic or the

Ukraine-Russia war made several unforeseen impacts over the renewable transition across the globe. Though the study considered such events in the modelling, the insertion of such calamities may be done with deeper and more sensitised coverage.

The quantification of several variables used in the model was challenging. For simplification, many assumptions were made, and several variables were poured into one in a few cases. Due to the lack of segregated data, it was done. However, better modelling could be achieved if precisely segregated data could be made available. For example, renewable budget allocation from the central government and carbon taxation may have some interconnections in the disbursement mechanism. If it could be precisely detected and segregated in the model, the findings may be more specific. However, since carbon taxation is still not playing a larger role in Bangladeshi transition compared to other variables, the model can be considered still plausible.

The study generated an array of practical policy recommendations (See section **Error! Reference source not found.**). The technoeconomic feasibility of each of the suggestions can be thoroughly studied with care before realising them. Smart grid augmentation, green power import, deployment of mass energy storage and local manufacturing capacity enhancement must be given substantial importance as they are the most crucial factors for achieving 100% renewable transition.

9 Conclusion

This PhD study focused on the fundamental inquiry to identify the priority areas currently influential and necessary in future to assist Bangladesh's transition towards a sustainable electricity infrastructure. To facilitate the nation's progress toward realising its green power vision in nexus to being a developed nation by the year 2041, the study aims to deliver a plausible understanding of the influence of various socioeconomic and technical factors on the transformation. This was accomplished by first completing an extensive review of the available literature on Bangladeshi geographic and geopolitical settings, its power sectors and agencies, renewable transition momentum, various transition modelling techniques and their applicability in achieving the incumbent research goals. It screened various modelling techniques and rationally framed a conceptual framework for a nonlinear-logistic transition capacity model considering several influential sociotechnical variables pertinent to the Bangladesh context. The framework considered a wide range of aspects and prospects that are associated with the transition to greener power systems. The list includes expected power demand, economic viability, historical trends of several sociotechnical influencers, and other pertinent green transition considerations that are specific to the setting of Bangladesh.

The simulations of the model revealed that given the current level of efficiency and transition rate, the initial assessment of the renewable electricity potential in Bangladesh (such as solar, wind, biomass, tidal, etc.) identified major obstacles in sufficing future electricity demand solely from local green resources. As wind is not promising as a feasible power source, solar is the only dependable green option for Bangladesh to date. However, in such a densely populated country like Bangladesh, the challenges of land scarcity and the necessity of massive ESS were unravelled through the initial assessment of the renewable energy potential and their availability patter in Bangladesh. A large amount of influence will be exerted on the power demand scenarios by a variety of factors, including seasonal shifts, variations in cooling loads, and presumed shifts in appliance use. The sociotechnical capacity for green power transition model incorporates several different components. These components include the identification and assessment of available resources, the analysis of economic growth patterns and projections, advancements in technology and global market trends, cross-border power sharing, trade policies, and other factors that exert an influence.

Taking into account the values that are projected for major influential variables, the model illustrates the capacity of the nation for technoeconomically supporting the largest possible amount of renewable energy at a particular period in the future. The model began by taking into account a total of seventeen different variables, each of which has the potential to have some kind of effect on the impending transition to a greener economy in Bangladesh. On the other hand, examining the issues of collinearity and correlation led to the conclusion that just nine variables should be used. In order to capture the trajectory of renewable electricity in Bangladesh, a logistic General Additive Model was developed in MATLAB and used data from the preceding decade. The composite GAM function was solved through the VAR model solver in MATLAB as the data set was a time series one and many variables showed nonlinear trends. This growth in renewable electricity in Bangladesh began to become significantly more prevalent in 2010. After that, the model was used to simulate and provide predictions on future transition pathways. The results of the simulation shed light on the effects as well as the extent of the influence that numerous factors had on the potential pathways leading to a more environmentally conscious economy. The study suggests a gradual rise in the proportion of renewable energy sources to be included in the total energy composition. One policy that can be implemented is the use of incentives such as tax breaks or subsidies for companies that invest in renewable energy sources. This can help offset the higher initial costs of transitioning to clean energy and encourage more businesses to make the switch. This recommendation is based on the findings that were collected from various sources mentioned in the thesis. This expansion ought to be directed by a variety of elements such as the rationally predicted rise in financial feasibility, the availability of land area, and the technology progresses that boost the overall effectiveness of suitable renewable systems within the country. These factors should all come into play.

According to the findings from the simulation, it is obvious that the following factors may be ranked regarding their extent of influence in the following order: foreign aid, energy storage price, system efficiency, direct green power import, carbon taxes, per capita income, renewable power budget, land acquisition of large solar plant (land availability), and renewable electricity pricing. After further investigation, the reality nexus was validated by comparing the results of a survey and an interview, which yielded equivalent conclusions. Following the completion of the research, recommendations were developed, and ideas were presented that were based on the findings (mentioned in the appendices). The purpose of this step was to aid policymakers and energy traders/managers in understanding the transition dynamics and optimise their plans to exploit multifaceted benefits. The policy suggestions included several essential operational procedures.

The model simulation findings suggest that policymakers should prioritise setting clear and ambitious targets for transitioning to renewable power sources, implementing policies and regulations that incentivise and support the development of renewable energy infrastructure, and investing in research and development of new technologies to further advance the transition. Governments can introduce regulations such as renewable portfolio standards (RPS), feed-in tariffs (FITs), and carbon pricing that require or incentivize companies to use renewable energy sources. Governments can ensure compliance by implementing strict regulations and penalties for non-compliance, offering incentives for companies that use renewable energy sources, and regularly monitoring and reporting on companies' energy usage.

To begin, there was an emphasis placed on expanding the amount of foreign aid and support provided to the country to enhance its resources. In addition to this, there was an emphasis placed on making the most efficient use of the rooftops of industrial buildings and linking the solar arrays that are located on residential rooftops. This strategy attempted to achieve the greatest possible overall electricity harvest while simultaneously reducing the requirement of agricultural land that was required for its implementation. It suggested that mass energy storage like battery systems would not become viable for Bangladesh before 2030 since then, according to the model Bangladesh will have economic affordability and the battery price will go further down to its feasible reach. Innovations like carbon capture or hydrogen fuel generation are still not feasible in the Bangladesh context; it has to wait for a reasonable nailing time. In addition, the recommendations emphasised the importance of giving preference to applications such as direct solar irrigation, which would lessen the dependency on the use of pricey batteries. Last but not least, the ideas intended to promote environmentally sustainable modes of transportation by making it easier to set up charging stations for electric vehicles that were powered directly by the sun. In addition, the study made a prognosis for the best times for the widespread implementation of mass energy storage once it becomes possible for the provision of baseload electricity.

Within this framework, the study demonstrated the possibility of modifying the optimum policy mix to hasten the transformation of Bangladesh at a rate that is five to eight times faster than the current "business as usual" trajectory. The technoeconomic improvement of the systems may bolster the transition rate further if the adopted systems are regularly updated. If all the policy recommendations are considered for enactment, the 100% renewable transition may be possible by 2055-2060. However, the biggest challenges will lie in land scarcity and green power imports from neighbouring states as multiple stakeholders are associated with it and most of the power generation will depend upon these if sustainability comes into consideration. International cooperation and collaboration can be fostered to accelerate the global energy transition by establishing a global framework for cooperation and collaboration that includes all nations and stakeholders. This framework should include policies and incentives that encourage the adoption of renewable energy technologies, promote energy efficiency, and support innovation and research in clean energy technologies. Therefore, Bangladesh must enhance its capacity in energy diplomacy and resilience in geopolitical harmony.

The thoughts and recommendations formulated and offered from this research will help policymakers have a better understanding of the deep linkages that exist between the many different factors that influence the transition process. This comprehension will help in the process of making educated judgments and developing complete strategies for the general adoption and implementation of renewable energy systems in various parts of Bangladesh. These processes will consider the existing resources and financial capacities.

John Maynard Keynes said, “The future is always unclear, and nothing is more disastrous than a rational investment program in an illogical environment”. Moreover, a nation of the developing world, such as Bangladesh, cannot afford the luxury of taking a significant risk in its energy sector right now, despite its highest honest concerns about environmental responsibility. Yet, it must prepare itself for the anticipated transition shock from now on, and for that, a comprehensive but explicit program for boosting renewable energy is required. It must thoroughly investigate individually every step it plans in the pathway of transition towards renewable power and energy. This research is a prelude to deducing a few significant acumens for establishing and implementing that strategy.

10 Appendices

10.1 Appendix: Interview Extractions

Question	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6	Participant 7	Participant 8	Remark
In your opinion, what are the prospective renewable resources available for power generation in Bangladesh? Do you have any ranking preference regarding the abundance and harvesting ease?	Solar, Wind, Hydro, Tidal, Biomass Hydro is saturated. Biomass is not feasible to date.\ due to critical fertility issues.	Solar, Wind, Hydro, Biomass Hydro is saturated and not extractable anymore.	Solar, Hydro, Wind, Biomass Hydro is saturated Biomass is challenging/not feasible to date.	Solar, Wind, Hydro, Biomass Hydro is saturated Biomass is challenging	Solar, Hydro, Wind, Biomass Hydro is saturated Biomass is challenging/not feasible to date.	Solar, Wind, Hydro Hydro is saturated Tidal for future	Solar, Wind, Hydro, Biomass Hydro is saturated	Mainly Solar and Wind. Micro-hydro is possible but with limited prospects.	Solar is ranked first according to all The wind is 2nd according to 5 Hydro is 2nd according to 4 and 3rd according to 4 Hydro is saturated according to most Biomass is still not feasible, according to 4
Are you aware of any existing comprehensive, methodical resource mapping and feasibility studies for renewables in Bangladesh?	Resource mapping Yes Not Comprehensive Not sophisticated Not reliable Feasibility Study Yes, but not comprehensive. Foreign Agency conducted, heavily biased towards their interests (business)	Don't know	No	Yes Comprehensive	Yes Comprehensive	Yes Comprehensive	Yes	Yes Comprehensive	Most participants are aware of resource mapping, which is a fact. In the last two decades, few agencies and researchers conducted resource mapping, particularly for wind and solar since the mapping projects and studies came up with conclusive assessments and results implying enriched prospects for green power transition in Bangladesh.

Is/was there any government-funded project for such mapping?	yes	Don't know	yes	yes	yes	no	yes	yes	The first project to map renewable energy availability regarding solar and wind was undertaken two decades ago.
Did any completed resource mapping influence policy decisions/changes?	Yes. The proposed solar roadmap is based on those mapping results.	Should be	Yes. Those reports influence the motivation for large solar plans.	Yes.	Yes	no	yes	yes	
Are there any drivers and barriers influencing renewable power policies in Bangladesh?	Policy, Fund, Aid, Technical capacity, System efficiency	Aid, Budget, Capacity, Carbon Tax	Foreign Aid, Budget, Incentives, Capacity	Foreign Aid, Fund, Policy (Incentivisation)	Aid, Fund, Capacity, Carbon Tax	Fund, Aid, Incentives	Aid, Fund, Capacity, Carbon Tax	Efficiency, Price, Fund, technical capacity	
In terms of overall cost/kWh, in relation to use in Bangladesh, how would you rank the following technologies? Fossil-fuel and Coal	Coal<Gas<LNG<Solar<wind<Diesel	Coal>Gas<Diesel	Gas<Coal<Solar<Wind<Diesel	Gas<Coal<Solar<Wind<Diesel	Gas<Coal<Solar<Wind<Diesel	Gas<Coal<Solar<Wind<Diesel	Coal>Gas<Diesel	Coal<Gas<LNG<Solar<wind<Diesel	Most interviewees still consider Gas the cheapest resource in terms of lCoE.
It is predicted that Bangladesh is highly likely to experience a severe climate change impact. How is Bangladesh's energy policy is considering this?	Not much concerned about the energy and power sector as its trifle amount of emission is not responsible for global warming. However, it'll focus on rehabilitation and food security primarily regarding that issue.	Bangladesh will prioritise energy economics based on energy access and consumption	Less likely to impact on energy and power sector.	Less likely to impact on energy and power sector.	Less likely to impact on energy and power sector.	Less likely to impact on energy and power sector.	Bangladesh will prioritise energy economics based on energy access and consumption	Less likely to impact on energy and power sector.	
What international support would Bangladesh require to address this issue?	If global community wants to regress the fossil-fuelled power in Bangladesh, it should directly invest in the greening the power sector of Bangladesh.	First world countries should be the main drivers of green transformation of our power sector. However, morality or ethics is not a	Grant, Donation, Tax Relaxation, Incentivisation, Migration	If global community wants to regress the fossil-fueled power in Bangladesh, it should directly invest in the greening the	Migration	Capacity Building	First world countries should be the main drivers of green transformation of our power sector. However,	Migration, FDI, Capacity Building, Grant/Aid	Interestingly, migration has been opined as one of the major option

		strong driver in the field of economics.		power sector of Bangladesh.			morality or ethics is not a strong driver in the field of economics.	
10% power import (of the peak generation capacity) has been fixed as a threshold rule by the Bangladesh government. Do you think there may have to be a greater flexibility in the future?	Yes	Yes. It must be.	Yes	Yes	Yes	No	Yes. It must be.	Yes
In relation to 10 above, what are your views around generation plants located in other countries?	There is chance and intention	It should be done. However, energy security is a concern.	Not feasible	There is chance and intention	There is chance and intention	Not feasible	It should be done. However, energy security is a concern.	There is chance and intention.
Is it possible for Bangladesh to achieve 100% renewable power generation by 2050?	No	No	No	No	May be	No	No	No
From your point of view, what actions are needed to maximize renewable power generation?	Policy, Fund, Aid, Technical capacity, System efficiency, Large-scale deployments, grid improvement	Foreign aid, Foreign Investment, Friendly policy	Aid, Fund, Capacity, Large scale deployments, grid improvement	Foreign Aid, Fund, Policy (Incentivisation)	Aid, Fund, Capacity, Carbon Tax, Large scale deployments	Fund, Aid, Incentives, grid improvement	Budget, Incentives, Aids, Large scale deployments	Efficiency, Price, Fund, technical capacity, Large-scale deployments
Could you please elaborate on the roles and responsibilities of the developed world and foreign donors in promoting renewable power in Bangladesh?	If global community wants to regress the fossil-fuelled power in Bangladesh, it should directly invest in the greening the power sector of Bangladesh. Manufacturing, Capacity Building,	OCED countries are solely responsible for the climate disaster from global countries. They should admit it and take immediate initiatives to mitigate it.	Grant, Donation, Tax Relaxation, Incentivisation, Migration Manufacturing, Capacity Building,	If global community wants to regress the fossil-fuelled power in Bangladesh, it should directly invest in the greening the power sector of Bangladesh.	Migration	Manufacturing, Capacity Building	Foreign investment is a foremost necessity. Grants and aids should be an indispensable responsibility of the high carbon-emitting states	Migration, FDI, Capacity Building, Grant/Aid
In your opinion, how can Land	Main factor	Very influential challenge.	Crucial	Crucial	Crucial	Crucial		Crucial

Availability affect the implementation of renewable power in Bangladesh?		However, we should make good use of the already available spaces first.						
In your mind, what are the probable difficulties in the transmission and distribution of renewable power in Bangladesh? How do you want to address the issue?	System development and improvement needed	Outdated transmission and distribution systems are the main challenge in the proper power supply to people. Smart grid and using good quality items are essential.	System development and improvement needed	System development and improvement needed	System development and improvement needed	--		System development and improvement needed
To your knowledge, have the government taken any innovative approaches to promote green power in Bangladesh? How is the government encouraging innovations and research in this field?	Encouraging but in the nascent phase	More concentration needed	Satisfactory	More concentration needed	More concentration needed	More concentration needed		More concentration needed
Do you think the current level of government investment in the sector is currently appropriate?	No		No	No	No	No		No
The market for electric vehicles is slowly expanding in Bangladesh as prices drop. Is Bangladesh going to address this transition? Is there a particular government plan regarding electricity supply	Concerning		No Concern	No concern	Concerning	No concern	Assisting the load distribution and supply at night	Assisting the load distribution and supply at night

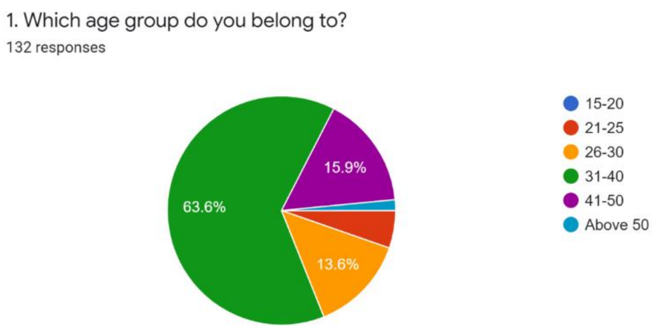
and grid stability to address this issue?								
To what extent do you think the massive deployment of renewable power may affect the energy security of Bangladesh?	Economic loss, Power Outage, Environmental Concerns regarding Battery Disposal		Power outage	Economic loss, Power Outage,	Power outage	Power outage	Power outage	Power outage
By when do you think Bangladesh can achieve 100% renewable power?	* 70-80 years more * No before 2090 * It'll not even achieve 100% by then. Perhaps nearly. *Not possible only with local resources.	* 80-90 years more * No before 2100 * It'll not even achieve 100% green by then. Perhaps nearly. * Only possible if a cross-border renewable grid is erected.	* 100 years more * No before 2120 * It'll not even achieve 100% by then. Perhaps nearly.	* 100 years more * No before 2120 * It'll not even achieve 100% by then. *International fossil fuel market will play a vital role.	* 80-90 years more * No before 2100 * It'll not even achieve 100% by then. Perhaps nearly.	* 70-80 years more * No before 2100 * It'll not even achieve 100% by then. *Geopolitics will play a vital role.	* 70-80 years more * No before 2100 * It'll not even achieve 100% by then. Perhaps nearly. *Not possible only with local resources.	* 70-80 years more * No before 2100 * It'll not even achieve 100% by then. Perhaps nearly.
Pick one factor that you think is the most influential in renewable power promotion in Bangladesh 1)Per capita income 2) foreign aid 3) Renewable Power Budget 4)energy storage price 5)system efficiency>direct green power import 6)land acquisition of large solar plant 7)PV power price 8)carbon taxation	Foreign grant	Foreign grant	Foreign grant	Foreign grant	Foreign grant	Land	Land	Foreign grant
How much electricity (maximum) may be imported from the neighbouring countries?	Not more than 10% of the total demand (Considering energy security)	Not more than 10% of the total demand (Considering energy security)	Not more than 10% of the total demand	Not more than 5% of total demand (Considering energy security)	Not more than 10% of total demand (Considering energy security)	Not more than 10% of total demand (Considering energy security)	Not more than 10% of the total demand (Considering energy security)	Not more than 20% of the total demand (Considering energy security)

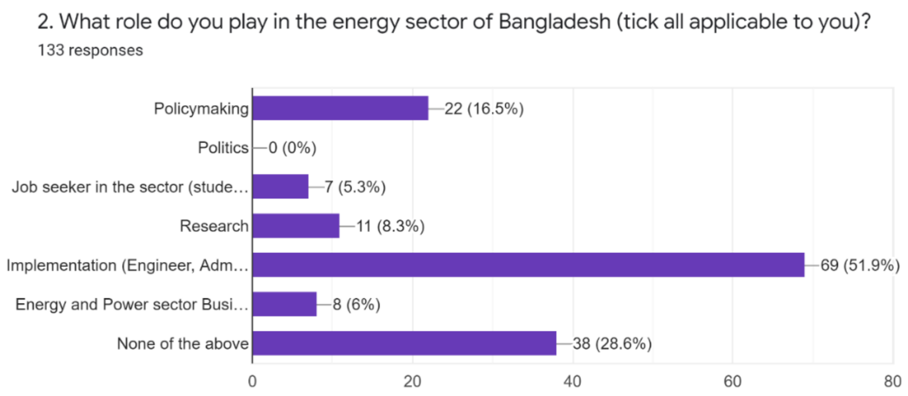
			(Considering energy security)					
What is Banglades''s position regarding carbon taxation?	It won't move without foreign compulsion.	It may impose a tax on carbon emitters to encourage renewables after 2030	Not before 2030. Perhaps earlier if foreign buyers compel.	No plan to date. Perhaps after 2030. Perhaps earlier if foreign agencies and importers compel.	No plan to date. Perhaps after 2030.	No plan to date. Perhaps after 2030. Perhaps earlier if foreign buyers compel.	No plan to date. Perhaps after 2030.	No plan to date. Perhaps after 2030.

10.2 Survey Results

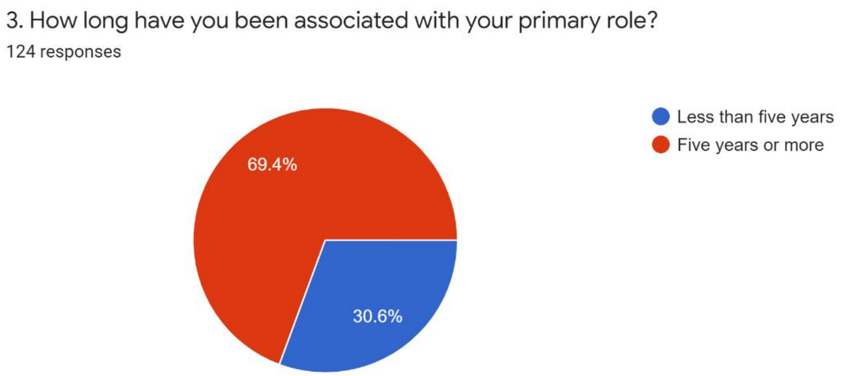
10.2.1 Respondent Particulars

Number of respondents 132

Particulars	Remarks
	The majority of the participants are from the range between 31-40. It is because of the following: • In the last ten years, many new engineers and administrators were recruited, appointed, and placed in Banglades''s energy and power sector to meet the workforce demand for the rapid growth of that sector (Situ, 2019). • Most of the newly appointed workforce were young (Situ, 2019) and are now between 31-40. The survey request was circulated among the policy-making bureaucrats, political policymakers, engineers, and administrators already actively involved in government power and energy policy-related issues. It was also circulated among the Electrical and Mechanical engineering students from the top institutes (Through Social Media Pages) of Bangladesh who is likely to be willing for prestigious jobs in the public administrative service/power sector because of its prestigious features in Bangladesh. The age range of 41-50 exerts the most significant influence over policy decisions. However, the younger participants would shortly replace them as well. Therefore, all of them are crucial in this survey.

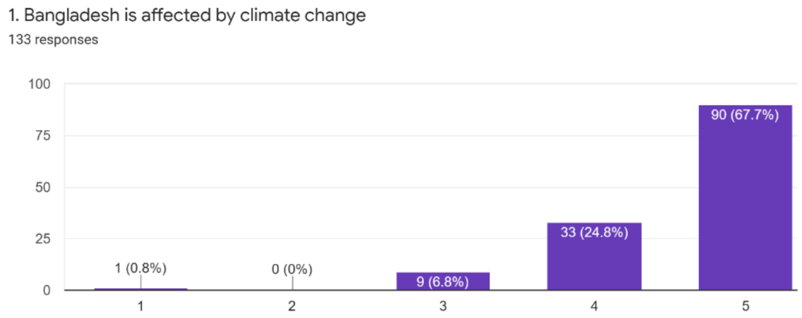
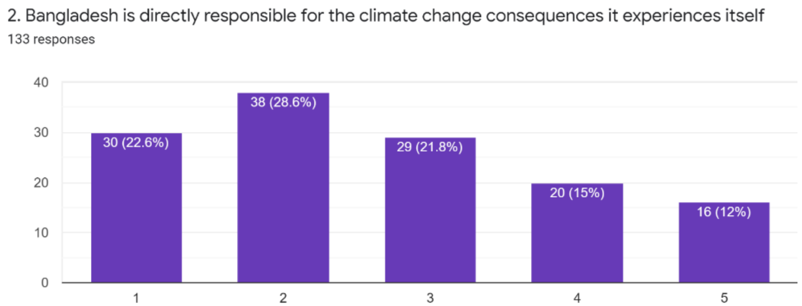


Most of the respondents (51.9%) were implementors, organisers and managers of various activities in the generation, transmission, and distribution of power in Bangladesh. They include engineers, managers, project directors, monitoring authorities, policy analysts and formulators, project planners and administrators. Since the generalist policymakers depend heavily on them in all steps for policy formulation, enactment, implementation and evaluation, the roles seem significant for this survey and the research.

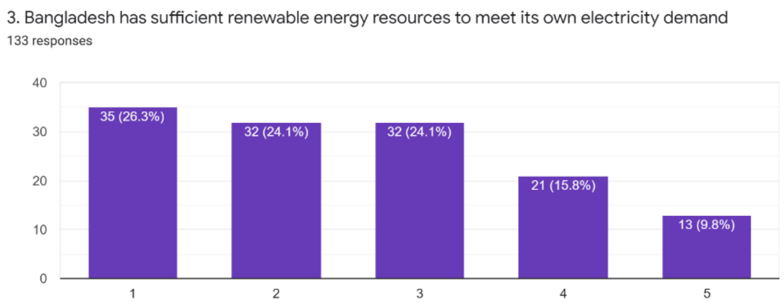


The response denotes that most participants have served the sector for five years or more, making their positions more significant for the study as they are more likely to influence policy decisions and directions.

10.2.2 Survey Questions and Responses

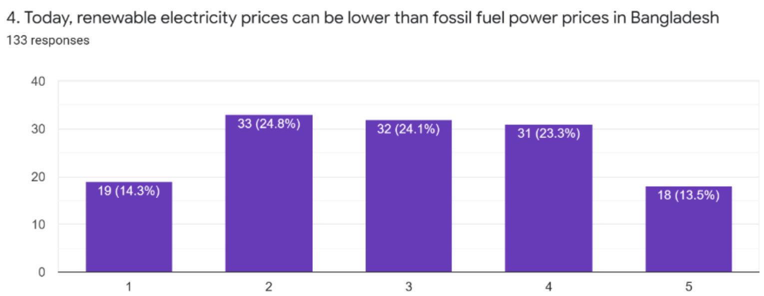
Questions and responses	Analyses	Remarks
	Nearly all the respondents agreed that Bangladesh is affected by climate change. It is strongly supported by several studies and evidence that Bangladeshi people directly face the challenges caused by the change.	If most respondents approved that Bangladesh is affected by climate change, it also links to the origin of the change, which is carbon emission from various power generation systems. Therefore, the opinion may exert a driving momentum towards adopting green power policies.
	The responses to this statement indicate a diverse range in understanding the fact behind this statement. However, most participants opined that Bangladesh is not responsible for its own.	The numerical data and facts denote that Bangladesh is one of the poorest energy users in the world in terms of per capita consumption. Naturally, the carbon emission is also very low compared to the high energy user countries[48]. Therefore, the responsibility still does not solely fall on its shoulder to date to any significant extent.

[48] https://earthjournalism.net/stories/bangladesh-pledges-to-reduce-22-carbon-emissions-by-2030



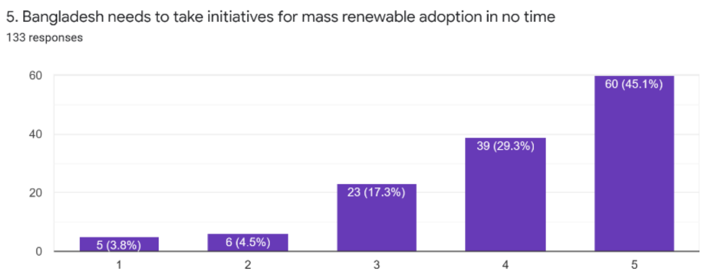
This feedback reflects a reasonably coherent understanding of the reality among the respondents about the green power prospect in Bangladesh, which has already been discussed with references several times in this thesis (See the ``Renewable potential in Bangladesh`` chapter).

Many studies confirmed that although Bangladesh has enormous solar power potential, land scarcity, high energy-storage prices, and lack of technical pragmatism will impede the prospect of 100% green power. Half the respondents (50%+) agreed that the potential is sufficient. However, many surveyees found it somewhat challenging.



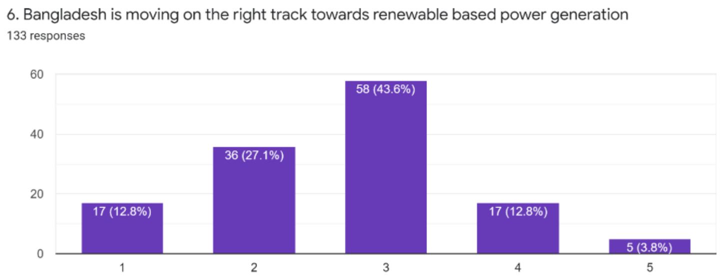
The feedback to this survey statement shows a mixed array of responses that signifies an ambivalent understanding of the questio''s subject matter. Renewable power pricing is done in two ways. One way counts the minimum supply capacity from a renewable power plant and pays the bill according to the MW of supply. Another way is to count the net electricity generated from the plant in MWh. Naturally, in the case of the highly fluctuating solar electricity, the first one earns less profit than the latter. However, the power system must include an energy storage accessory to ensure a consistent base-load supply from renewables adding to considerable costs. Therefore, the understanding of costs may have perspective duality among the respondents.

The consistent power supply from a renewable energy system, especially solar, requires ample energy storage. Additional energy storage systems like batteries cost a lot if the total energy is to be supplied from renewable sources. In Bangladesh, the payback period of a solar-battery system increases 4-5 times the fossil-fuel system's power price, considering the delivered electricity price (Khan, 2020). This fact may have confused the participants. Though schemes like ``net metering`` provide green power at a cheaper rate, an obligation of consistent flow from only green sources increases the price many times. These two options may have jumbled and hence produced a mixed response.



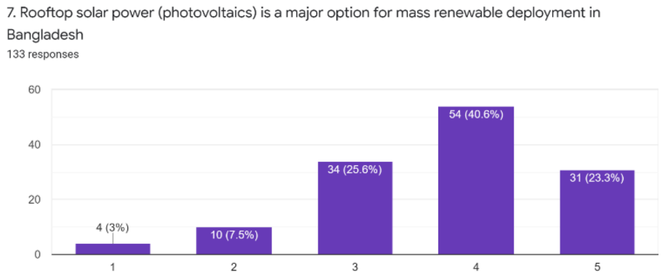
Most participants responded in favour of the urgency of disruption preparedness to avoid future transition shock. Among many countries across the globe, people are exhibiting progressive rises in awareness for renewable promotion that significantly bolstered the use of renewable in those regions (Ali *et al.*, 2019; Derasid *et al.*, 2021). Since most of the participants are young, educated and more likely to exert influence over policy decisions in th195mpedire, this response is favourable to the sustainable development of Bangladesh's power sector.

During the recent Ukraine-Russia war, fuel prices exhibited massive hikes worldwide. Policymakers already perceived that locally available free clean energy could significantly assist in shaving off the fuel price spikes. The rapid drop in renewable system prices and its engrossing technical advancement through the investors' growing interests in its R&D and production encouraged many stakeholders to go green at the earliest convenience. It quivered the public sentiments towards renewable power generation from locally available resources that can ensure energy security in many ways (Anisur Rahman, 2022).



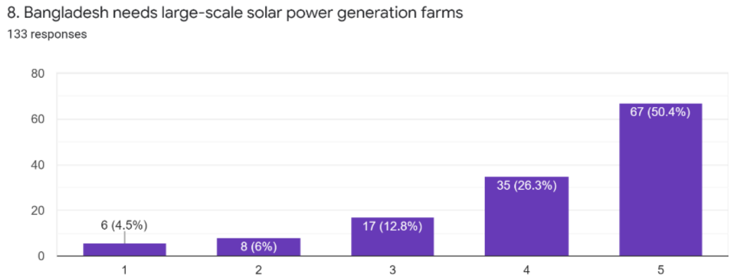
Due to the recent price hike in fossil fuels and the comparative advantages of some renewable systems, the Bangladesh government is expressing increasing interest in renewable transition. It also adopted and deployed many green power policies and initiatives. The installation and usage of 6 million solar home systems among rural premises have been declared a grand success (Kabir, Kim and Szulejko, 2017). Some large solar power plants have been erected and made operational[49]. However, many initiatives are not showing the expected success to date (Viktor, 2020). That may be the reason for the swinging response to this question. Most of the respondents could not take a side decisively.

However, the mode of challenges and the comparative advantages of fossil fuel systems over renewables are impeding its upscaling and stagnating the indecision among the decision-makers. Through many actions, Bangladesh has shown honest intentions to escalate its renewable share in its energy mix. Despite several challenges, it still barely uses its available sociotechnical capacity to green its power sector. The poll reflects this scenario.



This response denotes that a somewhat proper understanding of available renewable resources in Bangladesh is prevailing among the participants. Many studies reported the same (Halder *et al.*, 2015; Rahman *et al.*, 2016; Sohag *et al.*, 2020). This response also endorses the significance of the survey as the participants seem to have profound ideas of resource availability for transition in Bangladesh.

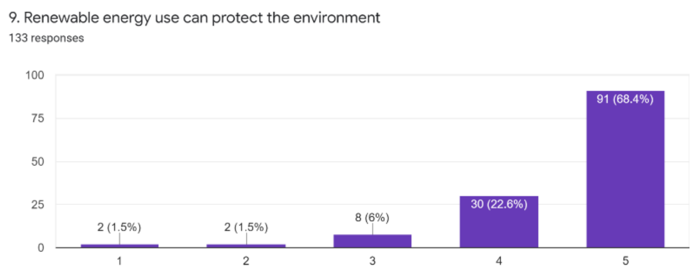
Strong responses favour the mass deployment of rooftop solar, implying two components. Firstly, it countersigns the respondent'' understanding of Banglades''s feasible solar potential. Secondly, they seem to know profoundly about the intense land scarcity in Bangladesh. That is why they cognised the maximum usage of rooftop areas for renewable escalation as a viable option.



Rooftop solar power systems at a small scale cannot provide the increasing demand of the rising population with escalating affordability. The appliances like air conditioners or refrigerators claim a lot of power. These commodities are demanded more yearly as global warming is kicking in, and people are earning more money to buy them. To meet the massive power demand of millions of people, large-scale solar plants are mandatory if Bangladesh wants to be sovereign in filling up its entire demand in greener ways.

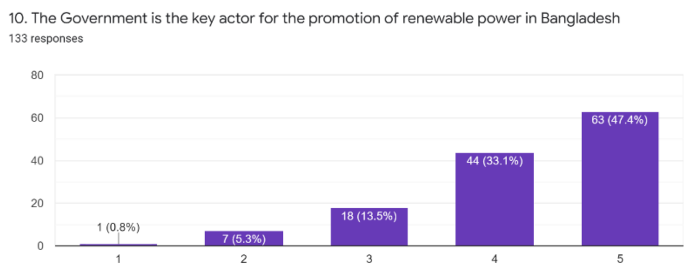
Though rooftop areas in households and industrial factory buildings may provide some spaces for solar electricity generation in Bangladesh, the spaces would not be adequate for consistently meeting the considerable power demand of a large population. Therefore, large renewable plants are required to ensure an incessant power supply at a large scale. Bangladesh has already approved the installation of several medium-to-large solar parks, and a few are already in operation[50].

[49] http://www.renewableenergy.gov.bd/index.php?id=1&i=1
[50] http://www.renewableenergy.gov.bd/index.php?id=1&i=1



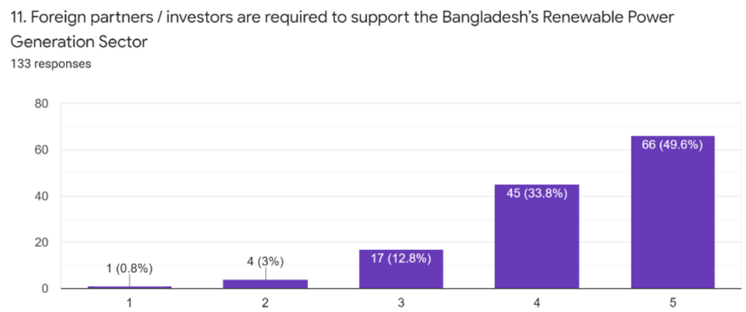
The response denotes a real insight from the people that renewable energy is eco-friendly. That is a fact, and the participants endorsed it as well. Most respondents were from technical backgrounds and likely knew the environmental advantages of renewable energy technologies.

Bangladesh has seldom taken environmental concerns seriously regarding the power generation programme to its utterly poor energy access (Asian Development Bank (ADB), 2013; Roy *et al.*, 2020). However, because of worldwide concerns regarding global warming and climate change and the resultant pressure from various groups, governments have started considering reducing carbon emissions from energy systems. The eco-friendly modus operandi of renewable technology and its growing economic feasibility encourage stakeholders to take it seriously.



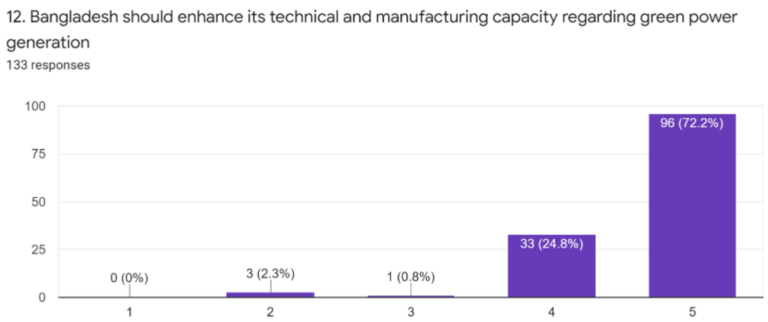
Most participants agreed on the government's key roles and responsibilities in the renewable transition in Bangladesh, which is a fact. For a developing country with poor affordability, private power producers are still less motivated to invest in green power generation, often subjected to lower rates of return.

It is a factual scenario in Bangladesh to date. In most developing countries like Bangladesh, governments are key players in power generation, distribution, and transmission. Government or government aides often take the initiative and advantages in such ventures due to their massive initial investment requirement that the private entities cannot afford. Even if some private entities enter the business, they do it by taking loans from public banks approved by the government. Unfortunately, because of several malpractices among the stakeholders, this has already been subjected to extensive disputes, particularly enormous capacity charges.



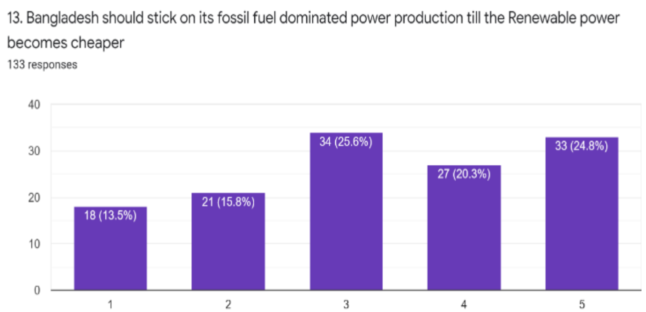
To date, foreign grants and aid have been Banglades''s major drivers of renewable power generation. If we investigate the milestones of renewable power generation in this country, both the hydroelectric power (1964) plant and the solar home system program (2010) were funded, initiated, and implemented with support from foreign donors.

This poll statement denotes the factually coherent historical concept about the main contributing factor for renewable power generation to date in Bangladesh among the responders. Since Bangladesh is one of the lowest carbon emitters but the worst victims of climate change, it rationally deserves more investment from developed economies with much higher carbon emissions than Bangladesh. Moreover, compared to fossil-fuelled power systems, renewable power prices are high when a consistent supply is required. It is due to the additional expenditure incurred in adding expensive energy storage.



It seems an optimistic and aspiring view from the participants on capacity enhancement for renewable technology deployment in Bangladesh. Bangladesh has already entered the solar panel manufacturing and printing of silicone modules. Many electrical and electronic engineers are showing interest in building careers in such a branch.

Recent graduation from LDC to a developing country pushed Bangladesh towards a wide range of light and heavy manufacturing and assembling activities, including producing electrical and electronic items. In that nexus, few firms have started manufacturing and marketing solar modules cheaper than imported ones. SREDA has launched an array of R&D activities relating to local renewable power generation technology manufacturing. However, to encourage such local manufacturing, the government has proposed taxes on imported solar modules that have already raised a drastic dispute[51]. The main reason for the disagreement is that local production is still insufficient to fill the rapidly rising demand for such products. Nevertheless, the government may revise the plan if such a policy sets the transition back198mpedingg the feasibility due to higher initial investment requirements.

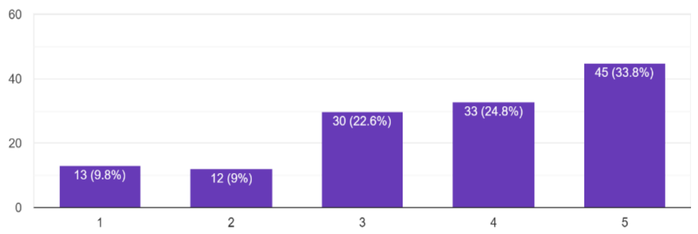


This feedback reflects somewhat dispersed opinions on the statement. Since fossil-fuelled power systems are still a reliable source of consistent power supply at a bulk rate, for a highly energy-poor country like Bangladesh, they are still prioritised to ensure 100% energy access by the policymakers. Therefore, land-scarce Bangladesh will likely face a dilemma about mass renewable deployment for baseload power generation when solar is the most abundant resource.

Policymakers and other stakeholders are still in a dilemma in Bangladesh regarding mass renewable deployment due to the less reliability of such systems. Moreover, the country is still nascent in providing minimum energy to fill civic needs. Therefore, the respondents feel it is not high time Bangladesh underwent a massive transition from fossil fuel to renewable power.

[51] https://www.businessinsiderbd.com/budget/news/23642/govt-imposes-tax-on-imported-solar-panel-to-protect-local-manufacturers

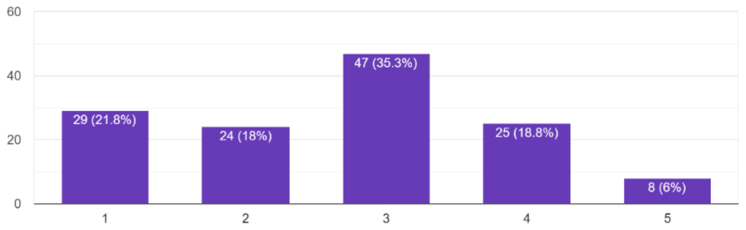
14. Bangladesh should reserve land for the installation of future solar plants right now as land is becoming scarce and more expensive
133 responses



This statement yielded relatively positive responses. The policymakers and other stakeholders were waiting for renewable resources to become cheaper and more reliable with technical advancement. The recent past trends for these criteria are thriving in positive vibes. The price of the modules or the storage systems is falling rapidly. It is likely to comprehend that even if a small amount of land surface is reserved now, the technically improved green systems installed on that piece are expected to deliver far more power at lower prices in the upcoming days than it currently does.

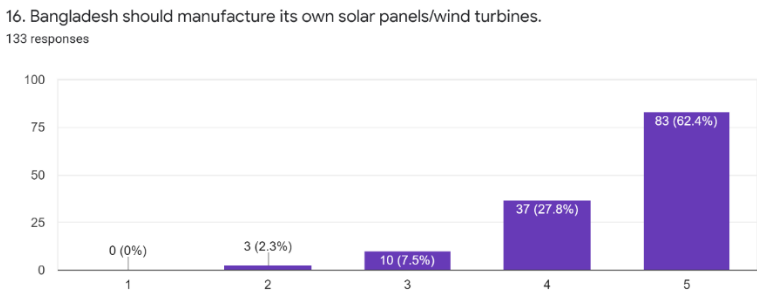
Recently, there has been remarkable progress in the efficiency augmentation of renewable systems. Perovskite solar cells invented at Oxford University can convert more than 30% of insolation to electricity (Rong *et al.*, 2018; Llanos *et al.*, 2020). Despite challenges, it is on the verge of commercialisation now. Similarly, all the components of renewable systems are becoming cheaper and technically more efficient through the massive investment in R&D for such endeavours. Therefore, a considerable number of respondents think that now a preserved land for such a project will pay off at a higher rate of return shortly when renewable options are more feasible. Perhaps they will not provide sufficient power right now, but in the future, they will. Therefore, land preservation is a significant postulation in this regard because of skyrocketing prices.

15. Bangladesh should try to bring renewable power from its neighboring countries
133 responses



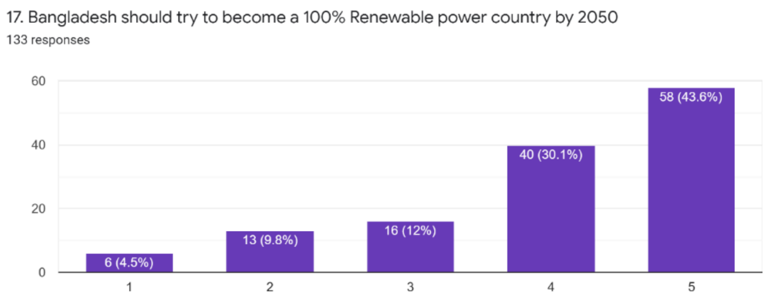
Bangladesh is an intensely overpopulated country, and its primary renewable resource is solar. Massive power generation from solar will require a lot of scarce and expensive land in Bangladesh. Bangladesh, predominately an agricultural economy, is still highly concerned about its food security for 180 million people. Though the rapidly booming country is in progressive need of power, replacing crop farms with solar or wind farms on food-supplying lands is still not feasible. However, since Bangladesh is already importing electricity from its neighbouring countries, it can propose the resource be renewables rather than fossil-fuelled. Bhutan and Nepal have plenty of hydroelectric potentials, which are more reliable than solar during monsoons. Bangladesh has already offered to install its hydroelectric plants in Bhutan and buy the power. This way, Bangladesh can enhance its renewable share without stressing its limited lands.

The respondents got divided into opinions due to a few reasons. Because of the erratic trends in the geopolitical stability of this subcontinent, the trusts between the states are still not forged with sufficient strength to rely upon electricity imports. In addition, the grid quality of Bangladesh is in its developing phase and incapable of handling the power tripping across the extraterritorial nodes. There are already several incidents of countrywide grid failure due to such tripping in Bangladesh. Therefore, policymakers have decided not to bring more than 10% of the total generation capacity from abroad concerning national energy security. These contemplations must have influenced the poll result here.



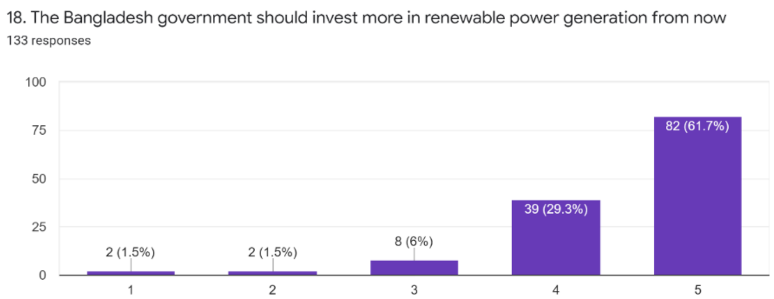
Developing the renewable technology industry in a region often promotes its propagation of use there, too (Wüstenhagen, 2017) and vice versa. It also depends on the abundance of renewable resources; in Bangladesh, it is solar. Manufacturing experience and expertise are essential to enhance the technical capacity in a true sense regarding renewable technology adoption.

Despite limited affordability and technical capability, Bangladesh initiated and publicly funded its R&D in renewable technology. Agencies like Energy and Power Research Council (EPRC) and SREDA (Sustainable and Renewable Energy Development Agency) are now conducting a wide range of research to explore the opportunities and potentials in various domains of the renewable energy sector. Some farms like Rahimafrooz have started to manufacture and assemble solar modules already. Some piloting studies on manufacturing small wind turbines at local workshops are in progress. Therefore, the stakeholders are also optimistic about the vast potential of this booming industry.



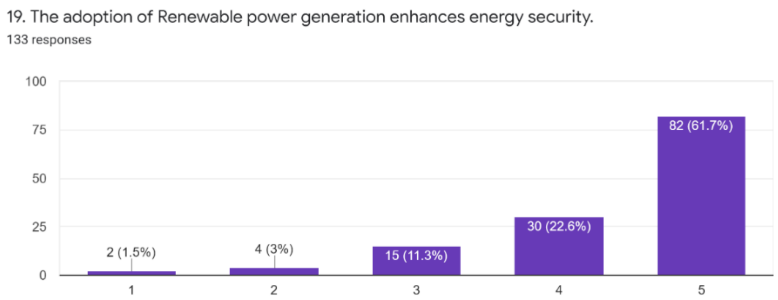
Many international organisations and climate activist groups warned the terrestrials to keep the temperature rise below 2^0 Celsius to tackle the devastating effects of climate change. The sustainable development goals (SDG) set the targets for going entirely green in the energy sector or conforming to a net zero world by 2050. In nexus with that, Bangladesh also aspires to clean its energy sector by 2050.

Bangladesh urged its policymakers and scholars to formulate pathways and roadmaps to attain the target by 2050. Despite a far cry, it has already contemplated, drafted and enacted several guidelines to escalate its renewable share in the energy mix with a diverse range of incentivisation approaches. Therefore, the endeavours are already on track. The sentiment may have influenced the poll.



In the past, most renewable energy initiatives were funded and supported by foreign agencies and donors in Bangladesh. However, as Bangladesh''s economic affordability is increasing, the country is becoming more capable of financing its renewable sector. Recently Bangladesh government has been encouraging and funding some solar and wind projects nationwide. Though foreign donors extensively support the schemes, a considerable portion of the fund is also coming from its local budget, and the amount is extending every year.

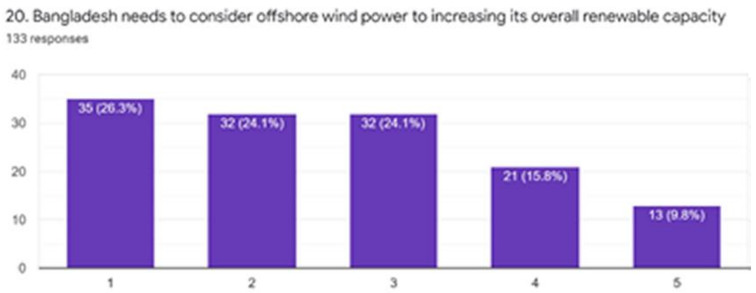
Since the global fossil fuel price is becoming erratic with several geopolitical issues, policymakers worldwide realised that local renewable resources are more reliable than exported fuels for ensuring

		energy security[52]. The same sentiment has also influenced the stakeholders in Bangladesh, and they are now encouraged and inclined towards renewable upscaling. As a result, progressive investment in renewable power generation occurs in Banglades’’s public and private sectors. The respondents extensively reflected their endorsement in favour of it.
	The lion’s s’are in the energy mix for electricity production comes solely from Banglades''s fossil fuel. It is rapidly consuming up its self-reserve, which is expected to become infeasible for extraction by 2030[53]. The increasing energy demand combined with rapid destocking is accelerating the dependency on fuel imports. The recent energy crisis and fuel price hike caused by the Ukraine war of 2022 compelled the government to adjust prices with international rates, profoundly threatening the energy security of a country with poor affordability like Bangladesh. These issues are persuading the policymakers and other stakeholders to think positively about the optimal uses of their renewable resources in Bangladesh for power generation. Local generation and use of renewable electricity can be an effective and timely option to ensure energy security at present and in future[54].	The sole source of fossil fuel used to produce power in Bangladesh makes up the lio’’s share of the energy mix. It is depleting its self-reserve quickly, and by 2030 it will be impossible to extract. The dependency on imported fuels is growing due to the rapid destocking and rising energy demand. The current energy crisis and gasoline price increase brought on by the 2022 war in Ukraine forced the government to raise tariffs in line with international standards, seriously jeopardizing Banglades’’s ability to meet its energy needs. These concerns encourage decision-makers and stakeholders to consider the best ways to utilise Banglades’’s renewable resources for power production. Using locally produced and renewable electricity might be a valuable and timely alternative to ensure energy security. Mainly, Solar power can take the role of fossil-fuel-based electricity throughout the day, compensating for the price spikes of the latter. These ideas may have vastly persuaded this poll result.

[52] https://www.cityam.com/solar-power-set-to-overtake-coal-as-war-in-ukraine-fuels-renewables-boom/

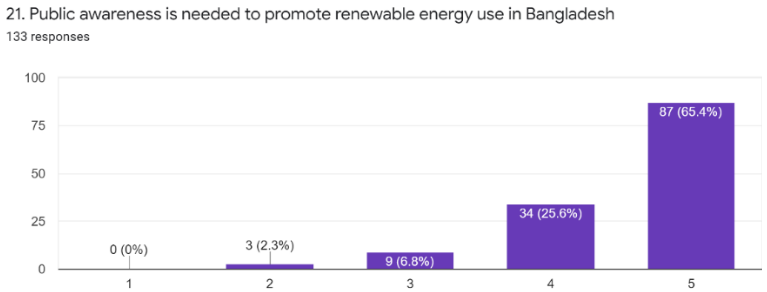
[53] https://www.thedailystar.net/environment/natural-resources/energy/news/bangladesh-has-gas-reserves-over-11-years-nasrul-3158076

[54] https://www.tbsnews.net/bangladesh/energy/solar-more-attractive-costs-less-furnace-based-electricity-experts-498862



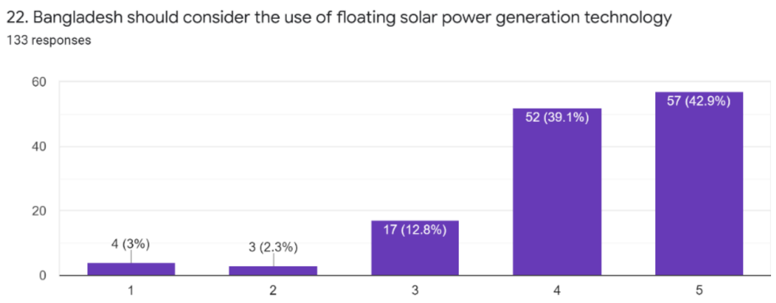
Bangladesh's onshore wind potential is subjected to many disputes due to the poor consistency of wind (Jacobson *et al.*, 2018). The nature of the wind that blows most of the time of the year is slow and unsteady. On the contrary, sudden gusts during coastal cyclones and seasonal tornados make the wind challenging to become bankable for power generation as the turbine poles require strong reinforcement to resist it. It would add more expense, diminishing the feasibility of such schemes in Bangladesh.

Offshore wind turbines could be a viable option for producing more consistent wind power but at a much higher installation and maintenance cost. Those are, at present, not affordable choices for the current developing economy. More extensive research is needed for significant policy and business decisions. Frequent cyclones arising from the Indian Ocean are another big challenge that may increase the budget for such ventures. During the summer and monsoon seasons (March to October), there can be very low-pressure areas, and storm wind speeds of 200 to 300 km/h can be expected. Wind turbines have to be strong enough to withstand these high wind speeds. However, wind can still be used in the energy mix to the optimum extent to endorse the sustainable energy transition based on techno-economic viability (Haque, 2018).



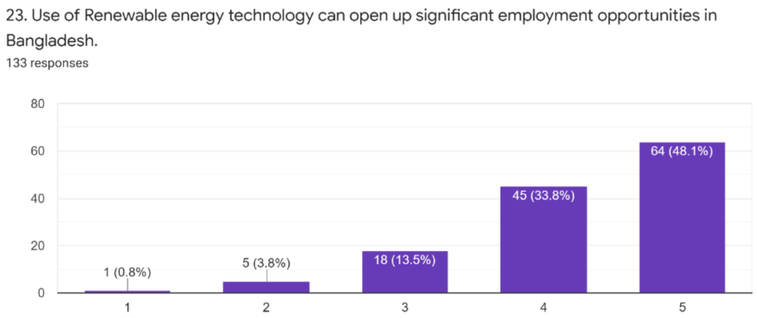
Public awareness is an influential driver in favour of renewable energy use worldwide. It has been proven to nudge political decisions in many countries. Though market and supply often control the propagation dynamics of renewable technology diffusion, public awareness is emerging as another solid force for its influencing capacity over the stakeholders. Moreover, people fall victim to climate change worldwide and face extreme adversities in many regions. Recent geopolitical unrests are also propelling the public mindset towards the mass adoption and deployment of renewable options as fossil fuels are becoming horrendously expensive abruptly. Moreover, as people become more educated and ethically enriched, a shift in the mindset towards environmental friendliness is also occurring among them.

Many factors influence the public mindset to prefer renewable energy over carbon-emitting systems nowadays. That is why the respondents have emphasised the power of public awareness towards green energy. The countr''s environmental activists also propelled the governmen''s recent announcement to go entirely green by 2050. Therefore, clean-energy movements have proved their capacity to influence decision-makers even in Bangladesh, where democratisation is still nascent. Consequently, this poll exhibited commensurate feedback.



Bangladesh is an intensely riverine country full of numerous water bodies. The freshwater bodies act like the lifelines of this Gangetic delta contributing in many ways. Since land is highly scarce here, many scholars contemplated installing solar modules on some of its water bodies. Some shallow studies were conducted to analyse the feasibility too. Unfortunately, some gave pessimist feedback about the potential, mentioning that the hazardous metalloids (arsenic, gallium, germanium, cadmium, copper, aluminium, etc.) from the solar modules may contaminate the water and its aqueous biodiversity[55]. However, hopes are still embarking as the modules can be made free from those materials and can be easily sequestrated.

Despite a few challenges like water contamination and investment security, Bangladesh is now seriously considering floating solar as a viable option for renewable expansion without stressing scarce land. Since land is minimal and a very crucial factor for the food security of a massive population, this option can be very significant for solar power generation in Bangladesh. The government and some other NGOs are now conducting several research on the feasibility of harnessing solar power from floating panels installed in the waterbodies of Bangladesh.

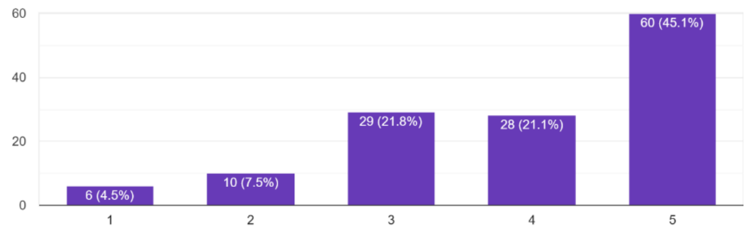


Most participants opined to some degree that renewable technologies could open and widen the doors for new employment. It is also already evident through several studies and surveys. The progress has also been upscaling over the last decade with a significantly consistent rate of rise (Sajid Yeamin, 2022).

As of 2022, more than 134,000 people are directly or indirectly employed through the business of renewable energy technology in Bangladesh (Sajid Yeamin, 2022). Upon observing the trend in the past decades, it is an exponential rise and likely to hike up more in the future. Moreover, the renewable aspirations among the responders in the poll endorse it substantially.

[55] https://businesspostbd.com/power-energy/adb-not-to-finance-kaptai-floating-solar-power-plant-39382

24. The priority for the adoption and use of Electric vehicles is to improve air quality in cites over to reduce carbon emissions.
133 responses



The feedback here implies that most participants are more concerned about the locally affecting environmental issues than the global ones. It is a widespread and logically normal perceptive psychosomatic reaction when a human group is affected locally by a worldwide crisis and feels less motivated to solve the global issue first. It also explains the prioritisation of rationale behind the use of electric cars, which was once exhibited when two-stroke engines were banned back in 2002 due to their dense emission that blackened the atmosphere of the cities in Bangladesh (Begum, Biswas and Hopke, 2006). The ban improved the air quality of the capital city within days. Therefore, mass public sentiment is not prioritising carbon emissions (in nexus to global warming) over locally perceived contemporary issues like an unbreathable atmosphere. It is an important indication that may be analogously implied in other challenges in the mass deployment of renewable technologies. Reducing carbon causing global warming comes later in peopl''s minds because its contribution to global warming is a trifle from Bangladesh. To date, the per capita carbon emission is still nominal in Bangladesh compared to most of the developed states. Therefore, people's mindset of Bangladesh still stresses other impacts of emissions (e.g. respiratory ailments) when considering its implications on the atmosphere and surroundings. The air quality of big cities is often dependent on the obnoxious exhaust gases from vehicles that directly inflict them. Electric vehicles can be an effective way to minimise those distresses faced by urban people.

10.2.3 Model simulation results vs data

Table 19 Collected Data vs Modelled Outcomes

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Renewable Power Generation (TWh) (Collected Data)	0.43	0.61	0.87	1.22	1.57	2.05	2.36	2.63	2.89	3.15	5,32
Modelled Outcomes (TWh)	0.359	0.578	0.865	1.078	1.586	2.329	2.5891	2.937	3.2186	3.3872	4.57
Difference (TWh)	0.078	0.038	0.049	0.128	-0.013	-0.28	-0.223	-0.31	-0.33	-0.234	-0.243
Difference (%)	19.77	5.53	0.57	13.17	-1.008	-11.97	-8.84	-10.45	-10.20	-7.00	-3.93

10.3 Conferences Attended and papers published

10.3.1 ICREN 2019, Paris, France (24-26 April 2019)

Presented a poster titled: TRANSITIONING BANGLADESH TO RENEWABLE POWER

Muhammad Talut, AbuBakr S. Bahaj and Patrick A B James, Energy and Climate Change Division, Sustainable Energy Research Group (www.energy.soton.ac.uk), Faculty of Engineering and Applied Sciences, University of Southampton, Southampton SO17 1BJ, UK

Abstract: This research addresses the question of what policies are required to guide and transform Bangladesh's current power supply into a low-carbon sustainable energy systems and infrastructure allowing it to become a developed country by 2041. A regression-based model simulation is being developed to exhibit the factors influencing the transition pathways. The model is addressing the share of renewable energy systems in the energy mix as a progressive penetration step supported by current and future technical advancements, coupled with financial requirements including affordability and renewable systems suitability for the country. This research outcomes are aimed at helping policymakers and energy planners to understand better the dynamic interrelations between different transitioning factors to allow for optimum planning of the wide-scale implementation of renewable energy systems according to the available resources and the fiscal potential of the regions in Bangladesh.

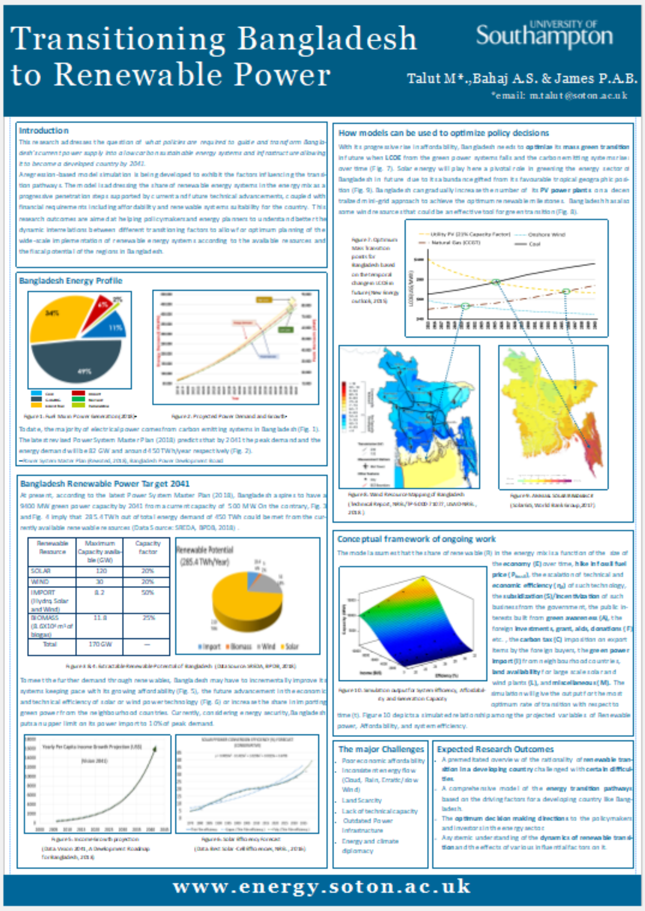


Figure 73 Poster for ICREN 2019, Paris

10.3.2 ICEC 2019 (July 2019, Southampton, UK)

Presented a poster titled:

SOLAR NET METERING TO SUPPORT RENEWABLE ENERGY EXPANSION IN BANGLADESH

Muhammad Talut, AbuBakr S. Bahaj and Patrick A B James, Energy and Climate Change Division, Sustainable Energy Research Group (www.energy.soton.ac.uk), Faculty of Engineering and Applied Sciences, University of Southampton, Southampton SO17 1BJ, UK

Abstract: Bangladesh is a developing country in South-east Asia with a consistent ~7% GDP growth rate over the last two decades. In its latest Renewable Energy Policy, Bangladesh made a promulgation to elevate its renewable share by 10% in its electrical energy mix by 2030. On the way to pursue this target, Bangladesh has enacted Solar Net Metering in 2018 to maximise its solar power harvest from the industrial prosumers enabling them to export the additional electricity generated from the solar system installed in their premise after self-consumption to the distribution grid. Bangladesh has severe land scarcity due to high population density and has a little scope for installing large-scale renewable power plants. Therefore, the net metering seems a very timely and effective technique to enhance the green power generation prospects of this country tackling the major challenge of land unavailability. Being a developing country and a global leader in producing certain commodities like garment, Bangladesh has a considerable number of medium to large production plants/mills/factories across its landscape occupying a significant portion of its available land.

The available rooftop areas of these industrial-scale entities are immense, providing a route for deploying large-scale solar PV systems by the affording prosumers. A methodology is developed to estimate these areas and predicted power generation. Data of the areas were obtained from the relevant ministries in Bangladesh. Using google maps as a starting point, the areas of fifty representative but randomly selected factories were measured providing a route to aggregation over the whole country. The results indicate that the estimated total extractable solar power from such premises is around 5 GWp with corresponding energy of 7.5 TWh that could contribute more than 6% of Bangladesh's current consumption. The initial analysis focused on displacing the power consumption of such factories and assessing the scope for power export to the national grid. Further improvement in the modelling will be carried out using GIS with power outputs linked to the local consumption of such factories.

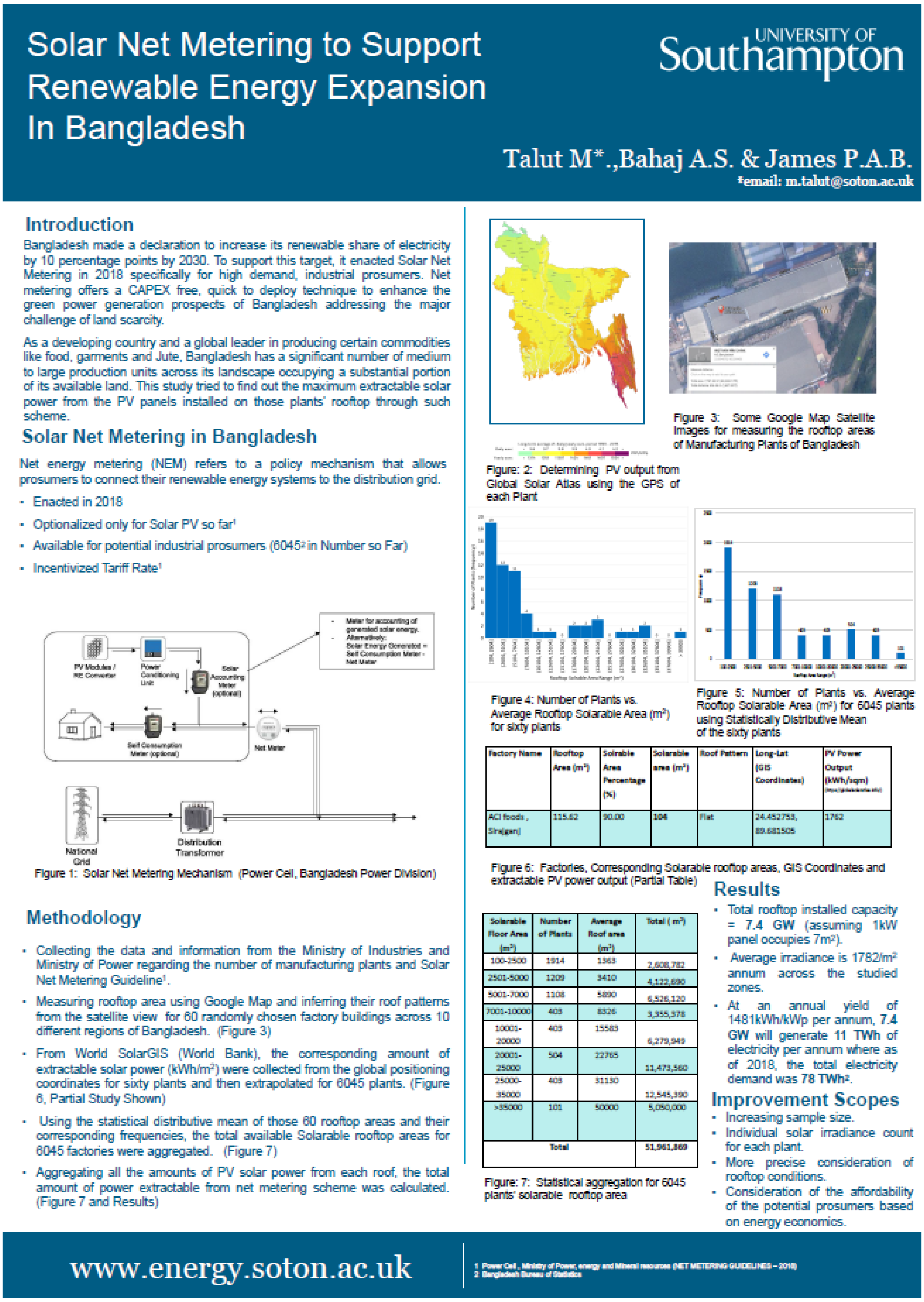


Figure 74: ICEC Poster

10.3.3 Paper: Solar Power Potential from Industrial Buildings and Impact on Electricity Supply in Bangladesh

by Muhammad Talut, AbuBakr S. Bahaj and Patrick James

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Abstract: Bangladesh's rapidly increasing population and healthy economic growth is resulting in a rising energy demand. The country also aims to increase its renewable share of electricity to 10% by 2030. However, due to limited wind resources, solar energy seems the most appropriate to deliver such a target. However, this presents a major challenge in a land-scarce country, which this work aims to address partially. Being a globally leading producer of commodities, Bangladesh has a considerable number of large manufacturing plants with appropriate roofs that could be used for deploying solar energy conversion systems at scale. A methodology is presented that identified and assessed 6045 such plants, which have roof areas ranging from 100 m^2 to 50,000 m^2, and modelled the deployment of solar photovoltaic (PV) technology to provide power through site-available grid infrastructure. Such deployment uses net metering regulations to enhance the case for such power generation. A techno-economic assessment addressed how such utilisation can support Bangladesh's 10% renewable target without impacting scarce lands. The results showed that around 7.4 GWp of PV capacity can be achieved on such roofs with a corresponding annual electricity generation of 11 TWh. It represents over 6% of Bangladesh's electricity consumption and over half of the 2030 target. Furthermore, the deployment will save 13,000 acres of farmland and provide power through site-available grid infrastructure, saving on investment if the systems are deployed on land. These results will likely influence policy to support the proposition, increasing the renewable energy share in the country's electricity supply mix and conserving much-needed agricultural land.

10.3.4 Sample Matlab Codes with some iterations

Script 1

```
function F = talsolver(k)
Rmax = 400;
global m;
% F(1) = (Rmax/(1+exp(-(k(1)*0.928+k(2)*0.95+k(3)*1.9+k(4)*0.15+k(5)*0.6+k(6)*0.4+k(7)*0.05+k(8)*0.2+k(9)*1.183+k(10)))))-.43;
% F(2) = (Rmax/(1+exp(-(k(1)*0.955+k(2)*1.0+k(3)*1.25+k(4)*0.20+k(5)*0.8+k(6)*0.5+k(7)*0.1+k(8)*0.3+k(9)*0.917+k(10)))))-.6132;
% F(3) = (Rmax/(1+exp(-(k(1)*1.054+k(2)*1.1+k(3)*1.2+k(4)*0.30+k(5)*1.0+k(6)*0.6+k(7)*0.2+k(8)*0.4+k(9)*0.721+k(10)))))-.876;
% F(4) = (Rmax/(1+exp(-(k(1)*1.184+k(2)*1.2+k(3)*1.1+k(4)*0.35+k(5)*1.5+k(6)*0.7+k(7)*0.3+k(8)*0.5+k(9)*0.663+k(10)))))-1.22;
% F(5) = (Rmax/(1+exp(-(k(1)*1.316+k(2)*1.3+k(3)*1.0+k(4)*0.40+k(5)*2.0+k(6)*0.8+k(7)*0.4+k(8)*0.6+k(9)*0.588+k(10)))))-1.5768;
% F(6) = (Rmax/(1+exp(-(k(1)*1.465+k(2)*1.4+k(3)*.97+k(4)*0.50+k(5)*2.5+k(6)*0.9+k(7)*0.7+k(8)*0.7+k(9)*0.381+k(10)))))-2.04;
% F(7) = (Rmax/(1+exp(-(k(1)*1.610+k(2)*1.5+k(3)*.83+k(4)*0.70+k(5)*2.6+k(6)*1.0+k(7)*0.9+k(8)*0.9+k(9)*0.293+k(10)))))-2.36;
% F(8) = (Rmax/(1+exp(-(k(1)*1.752+k(2)*1.6+k(3)*.71+k(4)*0.80+k(5)*2.8+k(6)*2.0+k(7)*1.1+k(8)*1+k(9)*0.219+k(10)))))-2.62;
% F(9) = (Rmax/(1+exp(-(k(1)*1.909+k(2)*1.7+k(3)*0.6+k(4)*1.00+k(5)*3.0+k(6)*3.0+k(7)*1.5+k(8)*2+k(9)*0.180+k(10)))))-2.89;
% F(10) = (Rmax/(1+exp(-(k(1)*2.12+k(2)*2.0+k(3)*0.4+k(4)*3.85+k(5)*3.5+k(6)*5.0+k(7)*2.5+k(8)*2.5+k(9)*0.124+k(10)))))-3.32;
```

```
F(1) = (Rmax/(1+exp(-(k(1)*m(1)*0.928+k(2)*m(2)*0.95-k(3)*m(3)*1.9+k(4)*m(4)*0.15+k(5)*m(5)*0.6+k(6)*m(6)*0.4+k(7)*m(7)*0.1+k(8)*m(8)*0.2-k(9)*m(9)*1.183+k(10)))))-.43;
F(2) = (Rmax/(1+exp(-(k(1)*m(1)*0.955+k(2)*m(2)*1.0-k(3)*m(3)*1.25+k(4)*m(4)*0.20+k(5)*m(5)*0.8+k(6)*m(6)*0.5+k(7)*m(7)*0.1+k(8)*m(8)*0.3-k(9)*m(9)*0.917+k(10)))))-.6132;
F(3) = (Rmax/(1+exp(-(k(1)*m(1)*1.054+k(2)*m(2)*1.1-k(3)*m(3)*1.2+k(4)*m(4)*0.30+k(5)*m(5)*1.0+k(6)*m(6)*0.6+k(7)*m(7)*0.2+k(8)*m(8)*0.4-k(9)*m(9)*0.721+k(10)))))-.876;
F(4) = (Rmax/(1+exp(-(k(1)*m(1)*1.184+k(2)*m(2)*1.2-k(3)*m(3)*1.1+k(4)*m(4)*0.35+k(5)*m(5)*1.5+k(6)*m(6)*0.7+k(7)*m(7)*0.3+k(8)*m(8)*0.5-k(9)*m(9)*0.663+k(10)))))-1.22;
F(5) = (Rmax/(1+exp(-(k(1)*m(1)*1.316+k(2)*m(2)*1.3-k(3)*m(3)*1.0+k(4)*m(4)*0.40+k(5)*m(5)*2.0+k(6)*m(6)*0.8+k(7)*m(7)*0.4+k(8)*m(8)*0.6-k(9)*m(9)*0.588+k(10)))))-1.5768;
F(6) = (Rmax/(1+exp(-(k(1)*m(1)*1.465+k(2)*m(2)*1.4-k(3)*m(3)*.97+k(4)*m(4)*0.50+k(5)*m(5)*2.5+k(6)*m(6)*0.9+k(7)*m(7)*0.7+k(8)*m(8)*0.7-k(9)*m(9)*0.381+k(10)))))-2.04;
F(7) = (Rmax/(1+exp(-(k(1)*m(1)*1.610+k(2)*m(2)*1.5-k(3)*m(3)*0.83+k(4)*m(4)*0.70+k(5)*m(5)*2.6+k(6)*m(6)*1.0+k(7)*m(7)*0.9+k(8)*m(8)*0.9-k(9)*m(9)*0.293+k(10)))))-2.36;
F(8)  = (Rmax/(1+exp(-(k(1)*m(1)*1.752+k(2)*m(2)*1.6-k(3)*m(3)*0.71+k(4)*m(4)*0.80+k(5)*m(5)*2.8+k(6)*m(6)*2.0+k(7)*m(7)*1.1+k(8)*m(8)*1-k(9)*m(9)*0.219+k(10)))))-2.62;
F(9)   =   (Rmax/(1+exp(-(k(1)*m(1)*1.909+k(2)*m(2)*1.7-k(3)*m(3)*0.6+k(4)*m(4)*1.00+k(5)*m(5)*3.0+k(6)*m(6)*3.0+k(7)*m(7)*1.5+k(8)*m(8)*2-k(9)*m(9)*0.180+k(10)))))-2.89;
F(10) = (Rmax/(1+exp(-(k(1)*m(1)*2.12+k(2)*m(2)*2.0-k(3)*m(3)*0.4+k(4)*m(4)*3.85+k(5)*m(5)*3.5+k(6)*m(6)*5.0+k(7)*m(7)*2.5+k(8)*m(8)*2.5-k(9)*m(9)*0.124+k(10)))))-3.32;

% F(1) = (Rmax/(1+exp(-(k(1)*0.928+k(2)*0.95-k(3)*1.9+k(4)*0.15+k(5)*0.6+k(6)*0.4+k(7)*0.1+k(8)*0.2-k(9)*1.183+k(10)))))-.43;
% F(2) = (Rmax/(1+exp(-(k(1)*0.955+k(2)*1.0-k(3)*1.25+k(4)*0.20+k(5)*0.8+k(6)*0.5+k(7)*0.1+k(8)*0.3-k(9)*0.917+k(10)))))-.6132;
% F(3) = (Rmax/(1+exp(-(k(1)*1.054+k(2)*1.1-k(3)*1.2+k(4)*0.30+k(5)*1.0+k(6)*0.6+k(7)*0.2+k(8)*0.4-k(9)*0.721+k(10)))))-.876;
% F(4) = (Rmax/(1+exp(-(k(1)*1.184+k(2)*1.2-k(3)*1.1+k(4)*0.35+k(5)*1.5+k(6)*0.7+k(7)*0.3+k(8)*0.5-k(9)*0.663+k(10)))))-1.22;
% F(5) = (Rmax/(1+exp(-(k(1)*1.316+k(2)*1.3-k(3)*1.0+k(4)*0.40+k(5)*2.0+k(6)*0.8+k(7)*0.4+k(8)*0.6-k(9)*0.588+k(10)))))-1.5768;
% F(6) = (Rmax/(1+exp(-(k(1)*1.465+k(2)*1.4-k(3)*.97+k(4)*0.50+k(5)*2.5+k(6)*0.9+k(7)*0.7+k(8)*0.7-k(9)*0.381+k(10)))))-2.04;
% F(7) = (Rmax/(1+exp(-(k(1)*1.610+k(2)*1.5-k(3)*.83+k(4)*0.70+k(5)*2.6+k(6)*1.0+k(7)*0.9+k(8)*0.9-k(9)*0.293+k(10)))))-2.36;
% F(8) = (Rmax/(1+exp(-(k(1)*1.752+k(2)*1.6-k(3)*.71+k(4)*0.80+k(5)*2.8+k(6)*2.0+k(7)*1.1+k(8)*1-k(9)*0.219+k(10)))))-2.62;
% F(9) = (Rmax/(1+exp(-(k(1)*1.909+k(2)*1.7-k(3)*.6+k(4)*1.00+k(5)*3.0+k(6)*3.0+k(7)*1.5+k(8)*2-k(9)*0.180+k(10)))))-2.89;
% F(10) = (Rmax/(1+exp(-(k(1)*2.12+k(2)*2.0-k(3)*0.4+k(4)*3.85+k(5)*3.5+k(6)*5.0+k(7)*2.5+k(8)*2.5-k(9)*0.124+k(10)))))-3.32;


% F(1) = (Rmax/(1+exp(-(k(1)*0.928+k(2)*0.95+k(3)*1.9+k(4)*1.5+k(5)*0.6+k(6)*0.4+k(7)*0.1+k(8)*0.2+k(9)*1.183))))-.43e-5;
% F(2) = (Rmax/(1+exp(-(k(1)*0.955+k(2)*1.0+k(3)*1.25+k(4)*2.0+k(5)*0.8+k(6)*0.5+k(7)*0.1+k(8)*0.3+k(9)*0.917))))-.6132e-5;
% F(3) = (Rmax/(1+exp(-(k(1)*1.054+k(2)*1.1+k(3)*1.2+k(4)*3.0+k(5)*1.0+k(6)*0.6+k(7)*0.2+k(8)*0.4+k(9)*0.721))))-.876e-5;
% F(4) = (Rmax/(1+exp(-(k(1)*1.184+k(2)*1.2+k(3)*1.1+k(4)*3.5+k(5)*1.5+k(6)*0.7+k(7)*0.3+k(8)*0.5+k(9)*0.663))))-1.22e-5;
% F(5) = (Rmax/(1+exp(-(k(1)*1.316+k(2)*1.3+k(3)*1.0+k(4)*4.0+k(5)*2.0+k(6)*0.8+k(7)*0.4+k(8)*0.6+k(9)*0.588))))-1.5768e-5;
% F(6) = (Rmax/(1+exp(-(k(1)*1.465+k(2)*1.4+k(3)*.97+k(4)*5.0+k(5)*2.5+k(6)*0.9+k(7)*0.7+k(8)*0.7+k(9)*0.381))))-2.04e-5;
% F(7) = (Rmax/(1+exp(-(k(1)*1.610+k(2)*1.5+k(3)*.83+k(4)*7.0+k(5)*2.6+k(6)*1.0+k(7)*0.9+k(8)*0.9+k(9)*0.293))))-2.36e-5;
% F(8) = (Rmax/(1+exp(-(k(1)*1.752+k(2)*1.6+k(3)*.71+k(4)*8.0+k(5)*2.8+k(6)*2.0+k(7)*1.1+k(8)*1+k(9)*0.219))))-2.62e-5;
% F(9) = (Rmax/(1+exp(-(k(1)*1.909+k(2)*1.7+k(3)*.6+k(4)*1.00+k(5)*3.0+k(6)*3.0+k(7)*1.5+k(8)*2+k(9)*0.180))))-2.89e-5;
% F(10) = (Rmax/(1+exp(-(k(1)*2.12+k(2)*2.0+k(3)*0.4+k(4)*3.85+k(5)*3.5+k(6)*5.0+k(7)*2.5+k(8)*2.5+k(9)*0.124))))-3.32e-5;



% F(1) = (Rmax/(k(10)+exp(-(k(1)*0.928+k(2)*0.95-k(3)*1.9+k(4)*1.5+k(5)*0.6+k(6)*0.4+k(7)*0.1+k(8)*0.2-k(9)*1.183))))-.43;
% F(2) = (Rmax/(k(10)+exp(-(k(1)*0.955+k(2)*1.0-k(3)*1.25+k(4)*2.0+k(5)*0.8+k(6)*0.5+k(7)*0.1+k(8)*0.3-k(9)*0.917))))-.6132;
% F(3) = (Rmax/(k(10)+exp(-(k(1)*1.054+k(2)*1.1-k(3)*1.2+k(4)*3.0+k(5)*1.0+k(6)*0.6+k(7)*0.2+k(8)*0.4-k(9)*0.721))))-.876;
% F(4) = (Rmax/(k(10)+exp(-(k(1)*1.184+k(2)*1.2-k(3)*1.1+k(4)*3.5+k(5)*1.5+k(6)*0.7+k(7)*0.3+k(8)*0.5-k(9)*0.663))))-1.22;
% F(5) = (Rmax/(k(10)+exp(-(k(1)*1.316+k(2)*1.3-k(3)*1.0+k(4)*4.0+k(5)*2.0+k(6)*0.8+k(7)*0.4+k(8)*0.6-k(9)*0.588))))-1.5768;
% F(6) = (Rmax/(k(10)+exp(-(k(1)*1.465+k(2)*1.4-k(3)*.97+k(4)*5.0+k(5)*2.5+k(6)*0.9+k(7)*0.7+k(8)*0.7-k(9)*0.381))))-2.04;
% F(7) = (Rmax/(k(10)+exp(-(k(1)*1.610+k(2)*1.5-k(3)*.83+k(4)*7.0+k(5)*2.6+k(6)*1.0+k(7)*0.9+k(8)*0.9-k(9)*0.293))))-2.36;
% F(8) = (Rmax/(k(10)+exp(-(k(1)*1.752+k(2)*1.6-k(3)*.71+k(4)*8.0+k(5)*2.8+k(6)*2.0+k(7)*1.1+k(8)*1-k(9)*0.219))))-2.62;
% F(9) = (Rmax/(k(10)+exp(-(k(1)*1.909+k(2)*1.7-k(3)*.6+k(4)*1.00+k(5)*3.0+k(6)*3.0+k(7)*1.5+k(8)*2-k(9)*0.180))))-2.89;
% F(10) = (Rmax/(k(10)+exp(-(k(1)*2.12+k(2)*2.0-k(3)*0.4+k(4)*3.85+k(5)*3.5+k(6)*5.0+k(7)*2.5+k(8)*2.5-k(9)*0.124))))-3.32;

% minusvalue = 330;
%
% F(1) = (Rmax/(k(10)+exp(-(k(1)*0.928+k(2)*0.95-k(3)*1.9+k(4)*1.5+k(5)*0.6+k(6)*0.4+k(7)*0.1+k(8)*0.2-k(9)*1.183))))-.43-minusvalue;
% F(2) = (Rmax/(k(10)+exp(-(k(1)*0.955+k(2)*1.0-k(3)*1.25+k(4)*2.0+k(5)*0.8+k(6)*0.5+k(7)*0.1+k(8)*0.3-k(9)*0.917))))-.6132-minusvalue;
% F(3) = (Rmax/(k(10)+exp(-(k(1)*1.054+k(2)*1.1-k(3)*1.2+k(4)*3.0+k(5)*1.0+k(6)*0.6+k(7)*0.2+k(8)*0.4-k(9)*0.721))))-.876-minusvalue;
% F(4) = (Rmax/(k(10)+exp(-(k(1)*1.184+k(2)*1.2-k(3)*1.1+k(4)*3.5+k(5)*1.5+k(6)*0.7+k(7)*0.3+k(8)*0.5-k(9)*0.663))))-1.22-minusvalue;
% F(5) = (Rmax/(k(10)+exp(-(k(1)*1.316+k(2)*1.3-k(3)*1.0+k(4)*4.0+k(5)*2.0+k(6)*0.8+k(7)*0.4+k(8)*0.6-k(9)*0.588))))-1.5768-minusvalue;
% F(6) = (Rmax/(k(10)+exp(-(k(1)*1.465+k(2)*1.4-k(3)*.97+k(4)*5.0+k(5)*2.5+k(6)*0.9+k(7)*0.7+k(8)*0.7-k(9)*0.381))))-2.04-minusvalue;
% F(7) = (Rmax/(k(10)+exp(-(k(1)*1.610+k(2)*1.5-k(3)*.83+k(4)*7.0+k(5)*2.6+k(6)*1.0+k(7)*0.9+k(8)*0.9-k(9)*0.293))))-2.36-minusvalue;
% F(8) = (Rmax/(k(10)+exp(-(k(1)*1.752+k(2)*1.6-k(3)*.71+k(4)*8.0+k(5)*2.8+k(6)*2.0+k(7)*1.1+k(8)*1-k(9)*0.219))))-2.62-minusvalue;
```

```
% F(9) = (Rmax/(k(10)+exp(-(k(1)*1.909+k(2)*1.7-k(3)*.6+k(4)*1.00+k(5)*3.0+k(6)*3.0+k(7)*1.5+k(8)*2-k(9)*0.180))))-2.89-minusvalue;
% F(10) = (Rmax/(k(10)+exp(-(k(1)*2.12+k(2)*2.0-k(3)*0.4+k(4)*3.85+k(5)*3.5+k(6)*5.0+k(7)*2.5+k(8)*2.5-k(9)*0.124))))-3.32-minusvalue;


% F(1) = (Rmax/(1+exp(-(abs(k(1))*0.928+abs(k(2))*0.95+abs(k(3))*1.9+abs(k(4))*1.5+abs(k(5))*0.6+abs(k(6))*0.4+abs(k(7))*0.1+abs(k(8))*0.2+abs(k(9))*1.183))))-.43e-5;
% F(2) = (Rmax/(1+exp(-(abs(k(1))*0.955+abs(k(2))*1.0+abs(k(3))*1.25+abs(k(4))*2.0+abs(k(5))*0.8+abs(k(6))*0.5+abs(k(7))*0.1+abs(k(8))*0.3+abs(k(9))*0.917))))-.6132e-5;
% F(3) = (Rmax/(1+exp(-(abs(k(1))*1.054+abs(k(2))*1.1+abs(k(3))*1.2+abs(k(4))*3.0+abs(k(5))*1.0+abs(k(6))*0.6+abs(k(7))*0.2+abs(k(8))*0.4+abs(k(9))*0.721))))-.876e-5;
% F(4) = (Rmax/(1+exp(-(abs(k(1))*1.184+abs(k(2))*1.2+abs(k(3))*1.1+abs(k(4))*3.5+abs(k(5))*1.5+abs(k(6))*0.7+abs(k(7))*0.3+abs(k(8))*0.5+abs(k(9))*0.663))))-1.22e-5;
% F(5) = (Rmax/(1+exp(-(abs(k(1))*1.316+abs(k(2))*1.3+abs(k(3))*1.0+abs(k(4))*4.0+abs(k(5))*2.0+abs(k(6))*0.8+abs(k(7))*0.4+abs(k(8))*0.6+abs(k(9))*0.588))))-1.5768e-5;
% F(6) = (Rmax/(1+exp(-(abs(k(1))*1.465+abs(k(2))*1.4+abs(k(3))*0.97+abs(k(4))*5.0+abs(k(5))*2.5+abs(k(6))*0.9+abs(k(7))*0.7+abs(k(8))*0.7+abs(k(9))*0.381))))-2.04e-5;
% F(7) = (Rmax/(1+exp(-(abs(k(1))*1.610+abs(k(2))*1.5+abs(k(3))*0.83+abs(k(4))*7.0+abs(k(5))*2.6+abs(k(6))*1.0+abs(k(7))*0.9+abs(k(8))*0.9+abs(k(9))*0.293))))-2.36e-5;
% F(8) = (Rmax/(1+exp(-(abs(k(1))*1.752+abs(k(2))*1.6+abs(k(3))*0.71+abs(k(4))*8.0+abs(k(5))*2.8+abs(k(6))*2.0+abs(k(7))*1.1+abs(k(8))*1+abs(k(9))*0.219))))-2.62e-5;
% F(9) = (Rmax/(1+exp(-(abs(k(1))*1.909+abs(k(2))*1.7+abs(k(3))*0.6+abs(k(4))*1.00+abs(k(5))*3.0+abs(k(6))*3.0+abs(k(7))*1.5+abs(k(8))*2+abs(k(9))*0.180))))-2.89e-5;
% F(10) = (Rmax/(1+exp(-(abs(k(1))*2.12+abs(k(2))*2.0+abs(k(3))*0.4+abs(k(4))*3.85+abs(k(5))*3.5+abs(k(6))*5.0+abs(k(7))*2.5+abs(k(8))*2.5+abs(k(9))*0.124))))-3.32e-5;
```

Script 2

```
clear all;
clc;
fun = @talsolver;
global m;
m = [1 1 1 1 1 1 1 1 1 1]; %multiplying factor
%% lsqnonlin
klim = 0.0001;
k0 = [klim klim -klim klim klim klim klim klim -klim klim];
options = optimset('TolFun',1e-5,'MaxFunEvals',500000,'MaxIter',1000000,'TolX',1e-9);
lb = [0 0 -90 0 0 0 0 0 -30 -500];
ub = [90 90 0 90 90 90 90 90 0 500];
k = (lsqnonlin(fun,k0,lb,ub,options))
%% fsolve
% k0 = [-1e-20   -1e-50   -1e-50    -1e-50    -1e-50   -1e-50    -1e-50   -1e-50    -1e-50    1e-50];
% k0 = [-1e-20   -1e-50   -1e-50    -1e-50    -1e-50   -1e-50    -1e-50   -1e-50    -1e-50];
% k0 = [5 6 -6 3 2 1 5 3 -1 0];
% k = fsolve(fun,k0)
%% iteration
Rmax = 400;
minusvalue = 0;
lastyear = 70;
for yyear = 1:1:lastyear
for yyear = 1:1:71
   year = yyear*0.1;
   income(yyear) = 15000/(1-16*exp(0.096*year))
   system(yyear) = (10*year+7.8)
    if system(yyear)>50, system(yyear)=50
    end
   pv (yyear)= -60*log(year) + 70
   aid (yyear)= (500/(1+743.5*exp(-10.5*year)))
   tax (yyear)=  -(31*year+3.3)
   green (yyear)= 42*year-8.5

   rbudget (yyear)= 23*year-5
   land (yyear)= 3.718*year - 0.9036
   if land (yyear) > 150, land(yyear)= 150
   end
   ess (yyear)= 1300*exp(-1.66*year)
   if pv(yyear) < 10, pv(yyear) = 10;
   end
   if ess(yyear) < 1, ess(yyear) = 1;
```

```
   end
   Rtotal (yyear) = Rmax/(1+exp(-(k(1)*m(1)*(income(yyear)/1000)+k(2)*m(2)*(system(yyear)/10)-k(3)*m(3)*(pv(yyear)/100)+k(4)*m(4)*(aid(yyear)/100)+k(5)*m(5)*(tax(yyear)/10)+k(6)*m(6)*green(yyear)/10+k(7)*m(7)*rbudget(yyear)/10+k(8)*m(8)*land(yyear)-k(9)*m(9)*ess(yyear)/1000+k(10))))-minusvalue;
end
plot(2020:2090,Rtotal,'k-')
hold on
y=1:71;
plot (2020:2090, (2.576.*y+ 2.3882))

xlabel('Year');
ylabel('Renewable Power Generation (TWh)');
(Rmax/(1+exp(-(x(1)*0.928+x(2)*0.95+x(3)*.280+x(4)*.15+x(5)*0.6+x(6)*0.4+x(7)*0.05+x(8)*0.2+x(9)*0.1183))))-.43
(Rmax/(1+exp(-(x(1)*0.955+x(2)*1.0+x(3)*.190+x(4)*.20+x(5)*0.8+x(6)*0.5+x(7)*0.1+x(8)*0.3+x(9)*0.0917))))-.613
```

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