



## Solar PV potential in Africa for three generational time-scales: present, near future and far future

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### ABSTRACT

Power outage is a regular occurrence in most African cities due to increasing energy demand from population growth and commercial activities outstripping the grid capacity. This results in disruption to normal life putting stress on businesses and affecting development across the continent. This review paper investigates the potential of solar photovoltaic (PV) in African cities from three perspectives. Firstly, the potential of rooftop PV in the context of the political, economic, social, technical, legal and environmental aspects (PESTLE) is evaluated. Thereafter, sustainable waste management of solar PV panels is reviewed in anticipation for the upcoming wave of end-of-life solar panels. Finally, the prospect of dual use building integrated photovoltaic (BIPV) as power generators and building components is investigated from case studies in Africa. Most studies highlight the strong potential of rooftop PV and BIPV due to the availability of high radiance in the continent. However, our review shows that affordability and lack of investment acts as a significant barrier to mass adoption of this technology which could be remedied by implementing appropriate energy policy and financing schemes. Alternative financing of PV products and service solutions such as leasing, pay monthly, pay-as-you-go, and subscriptions are emerging as popular options, and these approaches seem to act as drivers to market expansion. The review also emphasizes on the need for effective and sustainable waste management of solar PV products through implementing appropriately designed recycling schemes. This will need to be adopted now to ensure success and to prevent a waste management crisis in the future for the African continent.

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### Abstract

Power outage is a regular occurrence in most African cities due to increasing energy demand from population growth and commercial activities outstripping the grid capacity. This results in disruption

to normal life putting stress on businesses and affecting development across the continent. This review paper investigates the potential of solar photovoltaic (PV) in African cities from three perspectives. Firstly, the potential of rooftop PV in the context of the political, economic, social, technical, legal and environmental aspects (PESTLE) is evaluated. Thereafter, sustainable waste management of solar PV panels is reviewed in anticipation for the upcoming wave of end-of life solar panels. Finally, the prospect of dual use building integrated photovoltaic (BIPV) as power generators and building components is investigated from case studies in Africa. Most studies highlight the strong potential of rooftop PV and BIPV due to the availability of high radiance in the continent. However, our review shows that affordability and lack of investment acts as a significant barrier to mass adoption of this technology which could be remedied by implementing appropriate energy policy and financing schemes. Alternative financing of PV products and service solutions such as leasing, pay monthly, pay-as-you-go, and subscriptions are emerging as popular options, and these approaches seem to act as drivers to market expansion. The review also emphasizes on the need for effective and sustainable waste management of solar PV products through implementing appropriately designed recycling schemes. This will need to be adopted now to ensure success and to prevent a waste management crisis in the future for the African continent.

### **Highlights**

- The potential of rooftop solar photovoltaic (PV) in the context of the political, economic, social, technical and environmental (PESTLE) framework in Africa.
- The prospect of dual use of building integrated photovoltaic (BIPV) as power generators and building components in Africa.
- Implementing appropriate energy policy and financing schemes in African cities.
- Promoting a sustainable path for cost effective recycling and reuse of end-of-life PV in African cities.
- Supports in local capacity building and financial flow from the international development partners and multilateral agencies are crucial for African countries in the acquisition of such PV energy technologies.

### **Key Words**

Energy poverty, Africa rooftop PV, BIPV, End-of-life solar panels, sustainable waste management, sub-Saharan Africa

## **NOMENCLATURE**

### **Acronyms:**

**PV** - Photovoltaics

**BIPV** - Building integrated photovoltaics

**PESTLE** - Political, Economic, Social, Technological, Legal and Environmental

**IPCC** - Intergovernmental Panel on Climate Change

**SE4ALL** - United Nation's Sustainable Energy for All

**SDG** - Sustainable Development Goal

### **Subscript**

**Ag** - Silver

**Al** - Aluminium

**Cu** - Copper

**CT** - Cadmium telluride

**CIGS** - Copper indium gallium diselenide

**SiO<sub>2</sub>** - Glass

**Si** - Silicon

**Te** - Tellurium

**In** - Indium

**Ga** - Gallium

## 1.0 Introduction

Energy poverty is a major issue in many African countries including the cities. The electricity sector of the continent faces many challenges, such as insufficient installed capacity, frequent power outage, poor infrastructure and low economic resources for change. Coupled with the increasing threat from climate change and the need to meet the United Nation's (UN) Sustainable Energy for All (SE4ALL), clean power sources are crucial which are reliable and also affordable to all users. The UN Sustainable Development Goal 7 (SDG 7), which advocates providing universal access to clean, affordable, reliable and modern energy including the 600 million people to date mainly across the African continent who do not have access to electricity [1].

Solar energy is among the most accessible and abundant renewable energy sources, which can be utilised at different scales from few watts to several megawatts. Africa is particularly suitable for solar power generation because of the relatively high solar radiation within the continent [2–4]. Urgent need for such sustainable energy, carbon emission reduction and associated renewable technologies development and deployment have been highlighted at the Paris Agreement Conference [5] and COP-26 in Glasgow, where countries agreed to reduce their carbon emissions to tackle global warming. It was even more emphasised in the recent Intergovernmental [6] Panel on Climate Change (IPCC) report [7].

Studies have shown the potential of rooftop solar PV at city scale to cover most of a city's electricity demands whilst utilising existing space [8–11]. However, the majority of these studies relate to European cities, whereas there are only a handful of such studies covering African cities [10].

As a rule of thumb, with the prolonged sunlight hours and high intensity of solar radiation, African cities would be able to generate relatively high electricity yield from rooftop PV compared to other world regions [3]. Furthermore, rooftop solar PV can offer the benefit of allowing homes to be energy self-sufficient and independent from the grid, even in the case of frequent power outage from the weak or poor grids. Residential buildings with rooftop PV systems integrated with energy storage are more resilient to utility grid outage. Moreover, grid connected rooftop PV systems can export excess electricity generation to the utility network and increase the capacity of the local grid [8, 9, 12, 13] while making the investment more attractive for the building owners.

However, deploying rooftop PV in African cities at a wider scale would inevitably present many challenges, some of these are unique to the region. These challenges range across several socio-economic and technical parameters. This paper utilizes the PESTLE (Political, Economic, Social, Technological, Legal and Environmental) framework to investigate the opportunities, and also the challenges in deploying rooftop PV at a scale in African cities based on the available secondary data collected from recent literature and reports. The aim is to understand the potential for rooftop PV to meet the increasing energy demand in African cities and thus allow for a sustainable transition to the integration of increased renewable resources into the continent's energy mix.

With the increased applications of solar PV comes increased waste as the panels and other components get to the end of their life. At present most of these panels end up in landfills, especially in Africa where appropriate environmental recycling policies and regulation are yet to be key national renewable energy policy agenda. Reports [14,15] raised concern that disposal of the end-of-life PV panels will become an pertinent environmental issue in the next decade. Therefore, alternative reuse and recycling applications need to be considered. This paper also reviews the current progress of sustainable management for end-of-life solar PV in relation to Africa.

In addition to rooftop solar PV, building integrated photovoltaics (BIPV) is another technology to connect solar energy generation to buildings. The application of BIPV has the advantage of being used as a functional building element (such as a roof tile or wall) as well as an energy harvesting component. BIPV can be integrated to serve both the electrical and thermal loads of a building in some cases [16]. Although, this solar technology is yet to emerge as one of the mainstream applications, report [17] indicates that fast-paced solar technology development contributing to cost reductions and adaptation of carbon neutral climate policies will drive growth of BIPV. The potential

of BIPV in Africa is also investigated in this paper with reference to recent research in this field, which is limited and there is a literature gap.

The paper aims to address the key aspects of solar photovoltaic market to cover current and future situations. For example, while the application of rooftop solar photovoltaic at a scale is seen as a present challenge, with the system being used already in sub-Saharan Africa, PV panel waste management is a near-future challenge that requires planning from today. Whereas BIPV can be considered as a challenge further in the future, but still to be considered now for successful and sustainable implementation later on and to ensure that sub-Saharan Africa is at the forefront of this new technology applications.

Overall, this paper aims to provide insights into the current and future landscape, and applications of rooftop PV and BIPV technologies to address power outage issues in African cities. By identifying opportunities, addressing challenges and anticipating future considerations based on PESTLE framework and PV waste recycling it seeks to guide policymakers, investors, and stakeholders in fostering sustainable and equitable energy transitions across the continent.

This paper starts with an overview of the literature; thereafter the current challenges and opportunities associated with wide scale rooftop PV adoption in African cities is reviewed using the PESTLE framework. Following this, sustainable management for end-of-life solar PV is investigated. Then a future perspective of solar PV in buildings is considered through the evaluation of BIPV for Africa. Finally, the conclusion sums up the findings from the review and recommends further courses of action for policymakers. A research framework outline of the paper is presented below (Figure 1).

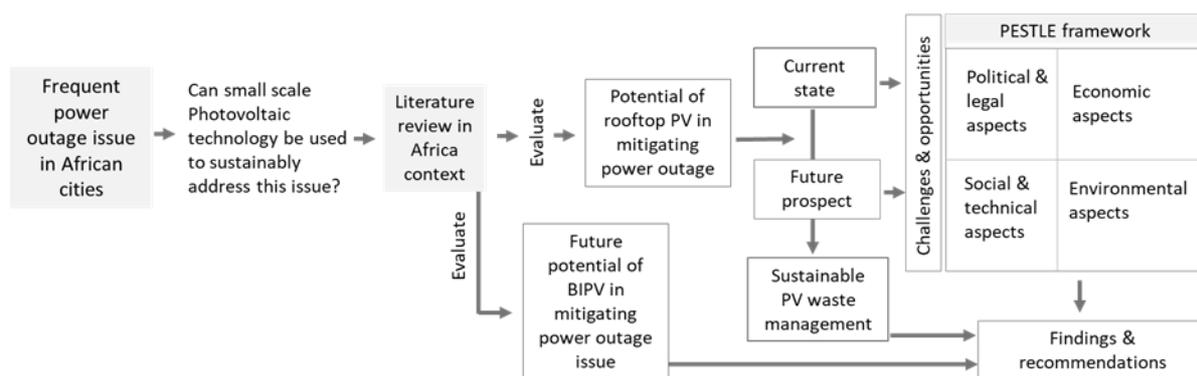


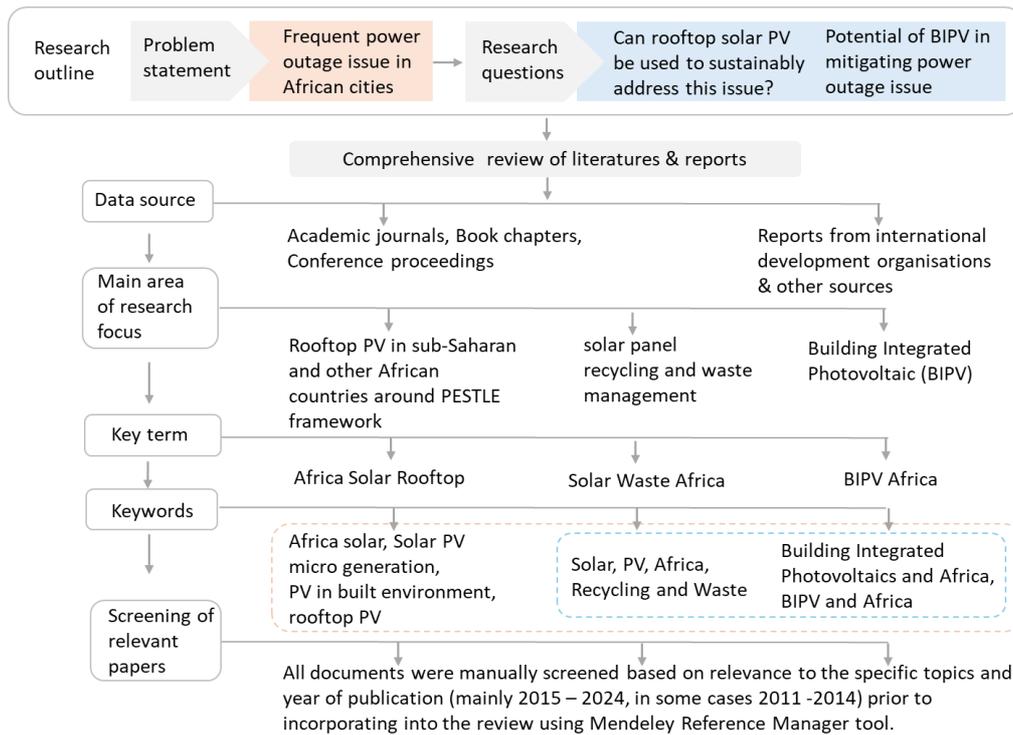
FIGURE 1 RESEARCH FRAMEWORK OUTLINE OF THE STUDY

## 2.0 Methodology

The methodology adapted for this review paper includes an in-depth search of related literatures and reports on the topic using range of specific keywords. The source data were mainly obtained from

scientific journals, i.e., ScienceDirect ([www.sciencedirect.com](http://www.sciencedirect.com)), CORE ([www.core.ac.uk](http://www.core.ac.uk)), IEE Explore ([www.ieeexplore.iee.org](http://www.ieeexplore.iee.org)), Springer ([www.springer.com](http://www.springer.com)), Nature ([www.nature.com](http://www.nature.com)) and Sage Journals ([www.sagepub.com](http://www.sagepub.com)) and edited book chapters. Besides academic papers and books, reports published by different organisations i.e., World Bank (WB), United Nations Agency for International Development (USAID), United Nations Environment Programme (UNEP), International Energy Agency (IEA) , Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), Energy and Environment Partnership (EEP), Department for International Development, African Development Bank (AfDB) and International Energy Agency (IEA). Relatively recent articles, mostly between the years 2015 and 2024 were reviewed to ensure up to date research results were considered. However, in some instances, data from literature and reports dated between 2011 and 2014 were also utilised where more recent publications were not accessible. The results were then manually screened to ensure each paper was relevant to the topic prior to incorporating into the review. Mendeley Reference Manager tool was used to import (automated and manual) all related articles, where filters can be used to identify papers or reports using specific tags.

Three areas were reviewed in detail. The first was the general state of rooftop solar PV in sub-Saharan and other African countries in relation to socio-economic and technical factors found within the PESTLE framework under the key term “Africa Solar Rooftop”. This included investigations into the prevalence of rooftop solar PV, energy policies, technological and other socio-economic factors. The following key search terms were adopted ‘Africa solar’, ‘Solar PV micro generation’, ‘PV in built environment’ and ‘rooftop PV’ under titles, abstracts and author-specified key words. The second area researched was solar panel recycling and waste management under the key term “Solar Waste Africa”. The search terms used were ‘Solar’, ‘PV’, ‘Africa’, ‘Recycling’ and ‘Waste’. On the specific journal webpages these terms were specified to be appear on the title, abstract or author-specified keywords. However, the terms ‘Solar’, ‘PV’, ‘Recycling’ and ‘Waste’ were specified to be appear in the abstract and the term ‘Africa’ in the full text. This was due to the limited search results otherwise. The third area researched was the prospect of Building Integrated Photovoltaic in Africa under the key term “BIPV Africa”. The search terms used were ‘Building Integrated Photovoltaics’ and ‘Africa’, ‘BIPV’ and ‘Africa’. The terms ‘BIPV’ and ‘Building Integrated Photovoltaics’ were searched for in the Abstracts and the term ‘Africa’ was searched for in the full article. The method applied for literature review approach for this study is summarized in Figure 2 below.



**FIGURE 2 METHODOLOGY APPROACH USED FOR THE STUDY. THE ROUND EDGE DOTTED RECTANGLES IN KEYWORD SECTION INDICATE PROBABLE OVERLAPS.**

Table 1 summarises the main search results under different key categories. The research papers were then reviewed individually and those that related to rooftop solar PV in an African city were considered for this paper. Nevertheless, only limited number of resources from other search results were available and included in this review. It is worth noting that for BIPV, some reference papers related to Asia were also used, given the limited research availability in African context.

**TABLE 1 RESULTS FROM SEARCH TERMS**

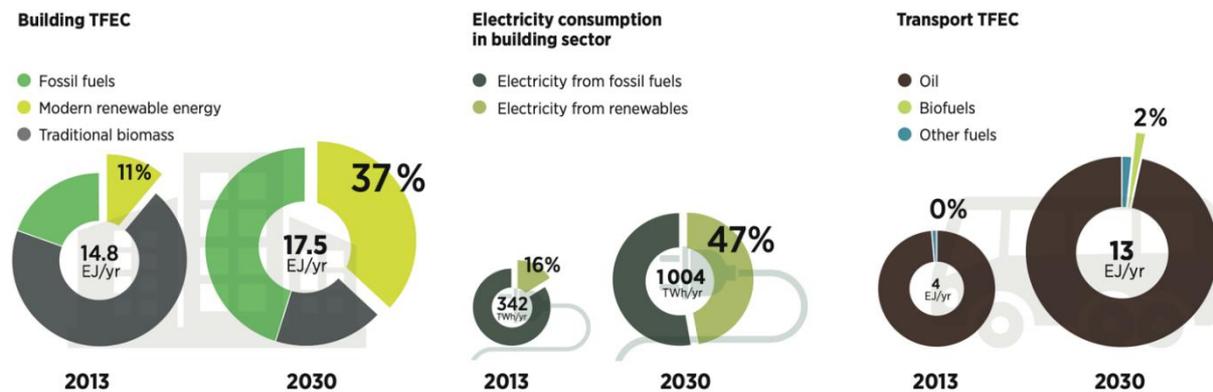
Search terms	Results - www.sciencedirect.com	Results - www.ieeexplore.com	Results – www.tandfonline.com
Africa Solar Rooftop	125	36	20
Solar Africa Waste	26	20	24
BIPV Africa	37	2	0

## 3.0 Rooftop Solar PV in Africa

### 3.1 Overview

Today, oil and gas exploration continue in Africa. With the economic growth in African countries, the demand for energy increases. This increases the incentives for oil and gas exploration [18]. However, oil and gas exploration needs to be considered in relation to climate change. When climate change

policy is evaluated in terms of African countries, North and South Africa are the best performing regions in terms of climate change [19]. Overall, there is ambition from African nations to move away from oil and gas by increasing the proportion of renewable energy in the building and transport sectors (Figure 3). Such as aiming to increase renewable energy proportion into the building electricity sector to 47% by 2030. However, such targets may be difficult to achieve at current progress, which is indicated in the case of South Africa’s net zero target 2030 [20].



**FIGURE 3 AFRICA RENEWABLE ENERGY TARGETS (EXAJOULE/YEAR) BY 2030 IN BUILDING TOTAL FINAL ENERGY CONSUMPTION (TFEC), ELECTRICITY CONSUMPTION IN BUILDING SECTOR AND TOTAL FINAL ENERGY CONSUMPTION (TFEC) IN TRANSPORT SECTOR [21]**

This highlights the needs to be more urgency from African nations on achieving net zero. A focus on renewable energy such as solar PV, can help Africa nations achieve their net zero targets and the UN Sustainable Development Goal 7 (SDG 7) for clean and affordable energy.

Installation, maintenance and operation costs of solar energy are cheaper compared to other renewable energy applications. For example, wind energy generation requires moving parts that need maintenance and have limited working life. In contrast, solar technology is simple to install, and PV panels have no moving components. The solar isolation potential of Africa is higher compared to other continents [3]. Therefore, solar energy can be an easy means of reducing greenhouse gas emissions from the energy sector in Africa and helping to limit climate change [22, 23].

To date, the potential of solar PV of different types (i.e, residential or utility scale) in Africa are still widely underutilized. Africa’s energy mix is currently mainly comprised of fossil fuels and biomass [24]. Traditionally in many African cities, diesel generators are used in homes as a back-up power source to supplement persistent unreliable utility grids across the continent. However, these are polluting regardless of their sizes and have high operating costs [25]. A comparison study [26] showed that for much of sub-Saharan Africa electricity from Solar PV could be cheaper when compared to diesel generators over the longer term. The lower capital investment (CAPEX) of diesel generator supersedes the high CAPEX of PV with its running cost related to expensive fuel. However,

the use of solar PV is projected to significantly increase in the coming years with the growth of energy demand in the continent [27]. This should also benefit African nations looking to achieve net-zero emissions and the SDG 7 for clean affordable energy, in the near future.

Many studies suggest the high potential for widespread grid tied rooftop PV to improve electricity generation capacity in African cities and provide self-sufficiency for buildings [2, 28, 29]. However, most of these studies are related to South Africa and Nigeria, with limited research elsewhere as presented in Table 2 below.

**TABLE 1 LITERATURE SURVEY OF AFRICAN ROOFTOP SOLAR PV STUDIES**

<b>Country</b>	<b>Title</b>	<b>Reference</b>
Nigeria	The potential of solar photovoltaic systems for residential homes in Lagos city of Nigeria	[30]
Uganda	Store-on grid scheme model for grid-tied solar photovoltaic systems for industrial sector application: Costs analysis	[31]
Tanzania	Investigating solar energy potential in tropical urban environment: A case study of Dar es Salaam, Tanzania	[9]
Egypt	Economic viability of rooftop photovoltaic systems in the middle east and northern African countries	[32]
Sudan	Economic viability of rooftop photovoltaic systems in the middle east and northern African countries	[32]
Morocco	Economic viability of rooftop photovoltaic systems in the middle east and northern African countries	[32]
South Africa	The impact of residential photovoltaic power on electricity sales revenues in Cape Town, South Africa	[33]
Nigeria	Cleaner energy in Nigeria residential housing	[34]
South Africa	Optimal energy cost and economic analysis of a residential grid-interactive solar PV system- case of eThekweni municipality in South Africa	[35]
Cameroon	Assessment of Building Integrated Photovoltaic (BIPV) for sustainable energy performance in tropical regions of Cameroon	[36]
Nigeria	Cleaner energy in Nigeria residential housing	[34]
Cameroon	A feasibility study of a residential photovoltaic system in Cameroon	[37]
Nigeria	Increasing household solar energy penetration through load partitioning based on quality of life: The case study of Nigeria	[38]
South Africa	Estimating the economic potential of PV rooftop systems in South Africa's residential sector: A tale of eight metropolitan cities(Article)	[39]
Nigeria	Solar energy harvesting on building's rooftops: A case of a Nigeria cosmopolitan city	[40]
Uganda	Feasibility assessment of grid-tied rooftop solar photovoltaic systems for industrial sector application in Uganda	[41]
South Africa	Effect on energy supply contribution by incorporating rooftop photovoltaic systems within the City of Johannesburg	[42]
South Africa	Rooftop Solar PV Potential Assessment in the City of Johannesburg	[43]
Namibia	Energy yield modelling of PV systems operating in Namibian conditions	[44]

Ghana	Cost-competitiveness of distributed grid-connected solar photovoltaics in Ghana: case study of a 4 kWp polycrystalline system	[45]
South Africa	Implementing building integrated photovoltaics in the housing sector in South Africa	[46]

The rest of this section presents the review of the literature with regards to identifying the various socio-economic challenges of rooftop PV in African cities using the PESTLE framework as mentioned earlier.

### 3.2 Political and Legal aspects

For rooftop solar PV to be widely adopted in African countries, appropriate supports should be provided by the Governments [2, 47]. This is related to the affordability factor, as the average African households would struggle to pay for rooftop PV without any financial support. Proven financial incentives, such as feed-in-tariff (FiT) subsidies, can only be instrumented through the use of related energy policy and regulations at national and regional levels. For example, studies have shown accelerated uptakes of rooftop PV through the introduction of FiT [48–50]. Such policy tools enhance dissemination of grid-tied rooftop PV power generation and lowers the cost of the electricity consumed by the home-owner in the long run.

There are various other forms of energy policy interventions to support uptake of rooftop PV, for example, tax reduction on solar products, financial contributions to households and net-metering schemes [51]. Most of the African countries are yet to adapt suitable and effective policy and regulations to promote such uptake. However the number of countries adapting energy policy schemes to support rooftop PV dissemination are increasing. Table 3 presents the list of some African countries which implemented energy policies to promote rooftop PV uptake.

**TABLE 3 ENERGY POLICY RELATED INTERVENTIONS FOR ENHANCING DISSEMINATION OF ROOFTOP PV IN DIFFERENT AFRICAN COUNTRIES**

Country	Policy Implemented	Status	Reference
Egypt	Feed-in Tariff.Net metering Scheme	In force. Mixed uptake. Feed-in tariff scheme reported to have ended and replaced with Net-metering scheme in early 2017.	[52,53]
Kenya	Feed-in Tariff	Slow / poor implementation. In place since 2008. However, did not contribute much to higher installed	[54]

		solar PV capacity due to poor implementation.	
Ghana	Financial Incentive. Net metering scheme. Feed-in Tariff	In force. To date 2.5 MWp installed. The FiT is guaranteed for 10 years and is stipulated in law.	[55]
Mauritius	Feed-in Tariff. Net metering and Incentives	In force. FiT is now closed for new applications as targets already met. Other schemes in place.	[56]
Seychelles	Tax incentives. Net metering and PV rebate scheme	In force. Tax incentives in place since 2001. Once rooftop PV installed, 25% of its cost can be claimed back from the government.	[56]
Comoros	Tax incentive	In force. Only scheme at present is zero tax for solar PV systems and products	[56]
Nigeria	Feed-in Tariff	In force Systems 1 MWp or above are covered under the current policy. Residential systems are yet to be included	[57]

There are limited success stories in Africa relating to effective rollout of policy to boost solar PV uptake. In Ghana, the government embarked on a project to provide free rooftop solar PV systems (up to 500 W) to help reducing demand on the national power grid [55]. The uptake was encouraging, and it was expected that 40,000 households will take part by 2030 adding 200 MW to Ghana’s electricity capacity [55]. This was also being supported by Net metering and FiT schemes [58]. Net metering for PV systems under 200kWp, which are applicable to residential sector came in force in 2015 with several other incentives contributing to 2.5 MW of solar PV being installed.

In Egypt, feed-in tariff rates were set by the government in 2014 and 2016, which allowed the system owners to sell excess electricity to the grid through a power purchase agreement [53]. However, the FiT rates were not attractive enough to initiate high PV uptakes [53]. Report by REREE [59] indicated that for the residential PV systems <200kWp FiT was determined as USD 0.053/kWh in 2016, which was changed to USD 0.065/kWh in 2018 for the same category. The FiT scheme has since been replaced by a Net metering scheme in which the government purchases the surplus electricity at the end of the year at the average cost of electricity production [52].

In Nigeria, enshrined within the framework of their energy efficiency policy a feed-in tariff strategy has been in place to encourage buildings owners to install as much as possible rooftop solar PV

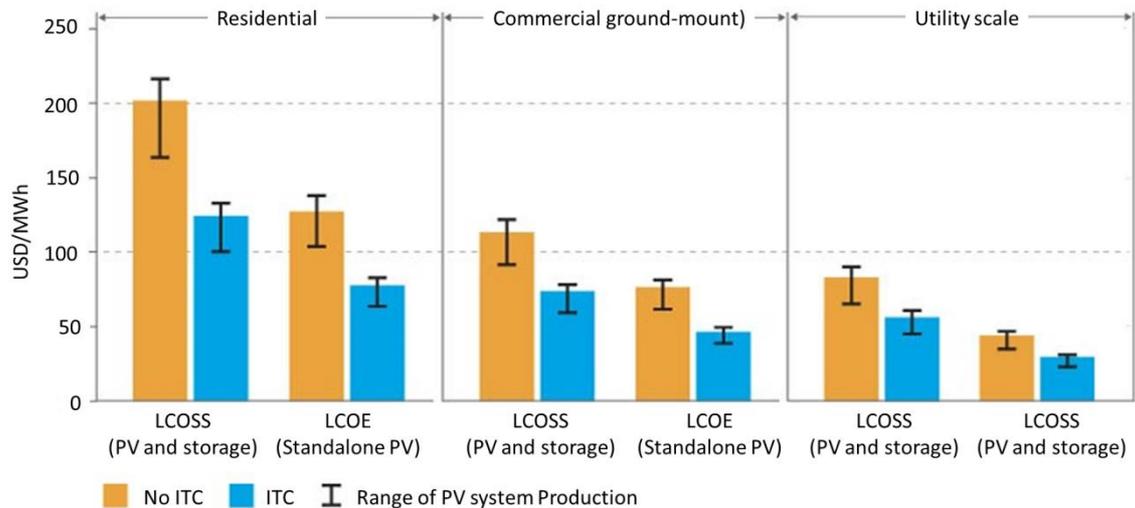
among other small-sized renewable energy systems [60]. However, discontinuity and poor implementation of energy policies are regarded as a major threat to successful solar energy integration in Africa [2]. For example, in Kenya, the feed-in tariff introduced had a lower uptake than expected, which is because of weak implementation of the policy [54], namely due to poor political will which is a major factor for success [61].

### 3.3 Economic aspects

Due to regular power outage, it is estimated that sub-Saharan Africa loses about 2.1% of its annual GDP, and the total sales of African firms falls by almost 4.9% as well [62]. This further proves the importance of reliable electricity supply. Government support of investment and regulatory tools to improve rooftop solar PV dissemination can complement the traditionally unreliable grids leading to better income for businesses and therefore higher tax revenue for governments.

Across literature, many researchers tried to put accurate economic feasibility studies of rooftop PV in African cities. Typically, the cost of electricity (COE) and the payback period are used to assess such feasibilities. It is worth noting that since the cost of PV panels along with the cost of the balance of the system have been decreasing over the years, it is expected that the COE will get closer to grid tariff. However, they are expected to differ due to the assumptions put in place in the estimations as well as the local supply chain factors. For example, solar panels from China are known to be cheaper compared to other regions, such as North America [63].

It should also be noted that both with or without energy storage, unit cost of installation of rooftop PV (residential or commercial buildings) is generally more expensive compared to utility scale solar farms (Figure 4) [64, 65]. This is mainly because of economies of scale for the latter where large amounts of solar panels are installed at proximity. Whereas for rooftop PV, installation happens at different properties each with additional time required to transport and install the panels.



**FIGURE 4 GRAPH COMPARING COST OF SOLAR PV SYSTEMS, WITH AND WITHOUT GOVERNMENT INVESTMENT TAX CREDITS (ITC). LCOSS DENOTES LEVELISED COST OF SOLAR PLUS STORAGE, AND LCOE DENOTES LEVELISED COST OF ELECTRICITY. [66]**

Unfortunately, the cost of solar PV systems is still considered out of reach for many residents in Africa [67]. The main barrier being the high initial capital cost (CAPEX). Furthermore, for the grid connected homes, subsidised low electricity prices from the grid makes the payback time for solar PV systems unattractive, particularly in many North African countries [32, 68]. An estimated payback period for a rooftop PV system in Cairo is over 20 years [32], which is mainly because of subsidised cheap electricity tariff from the national grid.

As discussed in section 3.2, African governments may use renewable energy related policy tools to provide financial incentives to building owners to adopt rooftop PV. Governments can raise funds for this through phasing out fossil fuel subsidies (whilst protecting the poor). Subsidies for fossil fuels are estimated to cost sub-Saharan Africa 5.6% of its annual GDP [24]

The private sector can also improve customer affordability through innovative financing tools. Some companies are combining technology with financing methods (Fintech) to make access to finance easier and more affordable [69]. Providers such as M-KOPA have reportedly sold over 1 million solar home systems (SHS) in Uganda and Kenya through pay-as-you go mobile payment schemes [70]. Although most of the solar home systems sold by M-KOPA are in the off-grid regions, the model is well accepted in cities and towns with more technological interventions. In South Africa and Zimbabwe, a scheme to fund solar home systems was done through community (zero-interest) loan sharing [71]. The projects were successful with 95% of on-time repayments; although the project was a non-profit and would be more suitable to government agencies.

### 3.4 Social and Technological aspects

Grid power outage, which is common among African countries negatively impacts the well-being of citizens [72]. In 2018, Nigeria and Niger reported some of the highest number of blackouts per customer, which were 304 and 289 respectively [72]. Although solar PV systems can help overcome these issues for individual consumers, it also comes with its own societal challenges, which may include (a) doubts about its ability to produce required electricity [73], (b) fears that it will be too expensive [29], (c) low trust due to reports of poor-quality components used [74], (d) low technical resource or poor knowledge transfer and training [28]. A recent study related to small scale PV systems in Sudan by Ahmed et al. [75] indicated that policy led quality control measure is necessary to build user confidence.

Furthermore, potential users may be put off by the report of poor-quality services received by friends or neighbours, which spreads as negative word of mouth. For example, if there is poor or no after sale services provided for the solar PV system then it could result in an under-utilized system that is not properly maintained [47,67]. This would depend on the solar PV vendors and installers, some of which may not have required technical skills and appropriate customer service trainings. Poor-quality solar components is one of the major issues in small and medium scale PV installations [74]. Such lack of trust in PV technologies would inevitably diminish building owners' confidence to invest in rooftop solar PV as their systems may break down in a short period of time. However, many solar PV suppliers and installers are now offering long term warranties on products to help build up trust.

On the other hand, several studies [75–77] have indicated the wider job creation opportunities provided by the small-scale solar industries, particularly in the off-grid sectors. For example, it was estimated that up to 350,000 jobs would have been created in the off-grid solar sector by 2022 in East Africa alone [75]. In addition to direct jobs, indirect employments are created along the supply chains, including in the building of necessary infrastructure [77]. Such opportunities could be created through the enhanced dissemination of rooftop PV in the cities of Africa.

Technological interventions in products and services can support fast uptake of rooftop PV. For example by providing new products, such as BIPV dual use material those are techno-economically suitable for African continent building integrated micro PV generation can be increased. On the other hand, through introducing innovative service schemes application of rooftop PV can be promoted, for example an 'Energy Storage on the Grid' system can improve the grid capacity. This involves multiple building owners installing rooftop solar PV and connecting these to a local energy storage unit provided by the government or utility. Electricity produced by the rooftop solar PV is used by the building users and any excess generation is sold to the grid. In Uganda, research [31] indicates that

around 12.5% reduction in the annual electricity purchase cost can be achieved for large scale rooftop solar PV through such systems [31].

### 3.5 Environmental aspects

The United Nation's (UN) target to reduce greenhouse gas emissions by 45% over the 10 years (from 2020 to 2030) is embedded in achieving zero emissions by 2050 by many countries [83]. A report by Castellano et al. indicates that if the sub-Saharan Africa region can fully switch to renewable energy sources by 2040, CO<sub>2</sub> emissions will be reduced by 27% [84]. Rooftop solar PV can contribute to this emission reduction pathway. However, sub-Saharan African countries excluding South Africa only have an accumulated capacity of 74 MWp rooftop solar PV as of 2019 [85].

Initiatives such as the Southern African Power Pool (SAPP) has developed a coalition of nine sub-Saharan countries to increase their renewable energy contributions and reduce their emissions [86]. The Grid Emission Factor (GEF), part of the SAPP, involves a study to determine greenhouse gas emissions for these countries based on standard baseline factors. As a result of the study, these countries will gain green certification or credit which in turn can help them get funding from the Green Climate Fund to further reduce emissions [87].

The benefits of clean electricity generation by the rooftop solar PV is well accepted. However, the emerging concern is the environmental impact during production of the solar panels (embodied carbon) and at the end of the solar panel's life. Most of the solar panels used in Africa are imported from China. Therefore, production level emissions are assumed to be negligible for Africa. However, as solar panels and related components are mostly non-recyclable this may create a significant landfill issue at the decommissioning of these panels. This topic is explored further in Section 4.

Based on the literature and reports examined, it is apparent that many African countries have not yet implemented suitable and effective policies and regulations to encourage the adoption of rooftop PV. However, there is a growing number of countries that already have initiated energy policy schemes to support the dissemination of this micro generation approach. Despite these efforts, significant successes in promoting rooftop PV uptake are yet to be observed. Nevertheless, key factors such as appropriate technology adaptations, creating fiscal incentive tools and introduction of environmental regulations are imperative to sustainably scaling up integration of rooftop PV in Africa.

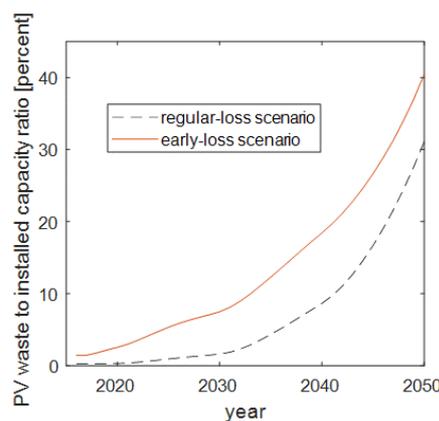
## 4.0 PV waste management and challenges

### 4.1 Overview

Solar PV panels have average lifetime of around 25 years before reaching their end-of-life. Many PV panels may fail in service before attaining the expected lifetime in many cases. A failed PV panel

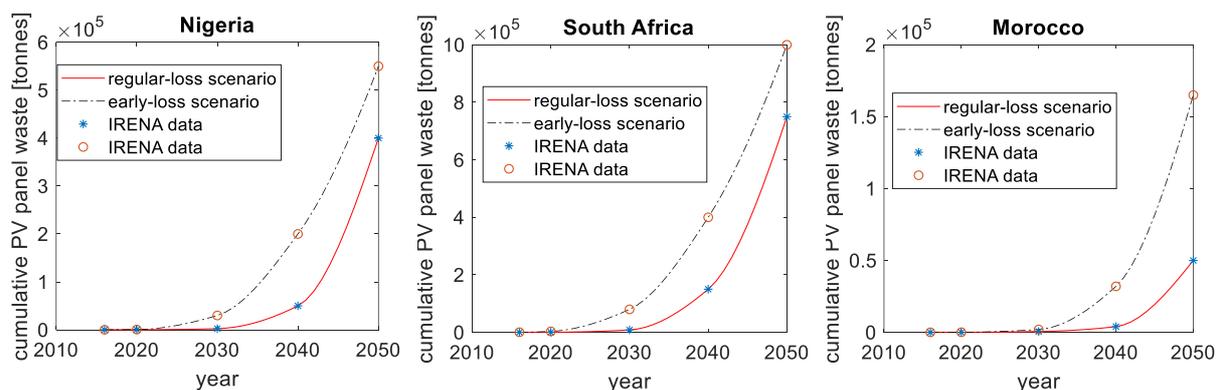
(i.e., damaged due to water ingress, failure of cells affecting performance of the whole string, mechanically damaged due to external factors) is also termed as its end-of-life PV panel. This is expected to be a mounting issue not just in Africa, but around the world. However, end-of life PV panel planning is very limited in African countries and the literature on the topic is sparse [88].

Many reasons are adduced for early failures of PV panels. According to a recent report [89], about 41% of PV panel failures result from degradation leading to breakage of soldered interconnections and/or cells due to thermal and mechanical agitations. About 45% of such failures result from corrosion due to moisture ingress under damp and humid exposures. Other failures result from degradation of polymeric components [90], manufacturing defects and thermal stresses at temperatures below the soldering and encapsulation temperatures [14]. As a result of these failures, end-of-life PV panel has become a mounting e-waste of global concern, not only in Africa [91]. It is reported that [92] at the global level, relative to new installations, end-of-life PV panel is estimated to be 4%-14% in 2030, and this percentage is expected to increase in the future as projected in Figure 5.



**FIGURE 5 PERCENTAGE OF PV PANEL WASTE TO INSTALLED CAPACITY [93]**

Using the country-specific data in [92] for Nigeria, South Africa and Morocco, and the interpolation method in [57], the projected end-of-life PV panel quantities are shown in Figure 6. The rising trends reflect rising yearly rate of addition of end-of-life PV panel which calls for concern.



**FIGURE 6 THE PROJECTED TREND FOR PV PANEL WASTE IN NIGERIA, SOUTH AFRICA AND MOROCCO [93]**

While end-of-life PV panels can be of economic value because of the re usability and recyclability of some of the components, they are a source of toxicity concern and environmental pollution [93]. Unfortunately, awareness and efforts in Africa to curtail the negative implications of end-of-life PV panel have not developed enough across the PV-specific waste management policies and regulations [92]. However, some African countries-initiated action plans in this regard. Ghana has introduced the eco-levy policy for all imported electrical and electronic equipment, including solar products since November 2018, whereby a minimum of USD 8 is levied on solar home system kits. In several other sub-Saharan African countries, the existing regulatory provisions on e-waste have been extended and adapted for the end-of-life PV panels, and such countries include Kenya, Rwanda, Uganda, and Nigeria [91]. It is clear that there is an urgent need to formulate and ratify policies for solar PV-specific waste management in Africa. The push for such policies will face the barriers of insufficient data on the waste quantities, poor infrastructure, limited awareness of the health and environmental impacts and the economic benefits, weak stakeholder engagement and lack of enforcement.

As a result of poor infrastructure in waste incoming framework and unavailability of PV waste-specific treatment facilities and infrastructures, end-of-life PV panels are currently treated in the existing e-waste treatment facilities, usually in separate batches [94]. This report [94] recommended that regulatory, fiscal and technical support frameworks need to be established first for PV waste-specific treatment plants to be effective and economically sustainable since that will guarantee that sufficient volumes of waste panels are collected and fed into the plants for full scale operation. Thus, this type of waste recycling may attract probate and public-private investment for longer term sustainability. Moreover, dedicated treatment plants will guarantee better quality recovery and higher quantity recovery of reusable materials from panels, increasing profitability. Thus, a comprehensive recycling infrastructure will result in optimum environment friendly operations for the whole PV products supply chain.

Assessment of specialized recycling of end-of-life PV panels showed likelihood of increased value of recovered materials when compared to manual recovery process, as reviewed in Ethiopia [95]. In Nigeria, it has been argued that businesses in PV waste management should be granted the 'pioneer status' under the law of the Federation of Nigeria that allows a seven-year tax holiday to pioneering industries located in the economically disadvantaged areas [93]. Extending such recommendation, other African countries should explore their existing legal provisions that potentially aide end-of-life PV panel management while formulating specific regulations and fiscal incentives to sustain the growth of this industry. To tackle the potential barrier of insufficient data on the solar PV waste quantities in Africa, it is recommended that policy development should expand the responsibility of

national bureaus/agencies of statistics or the other related authorities to develop comprehensive data driven insight regarding the potential of end-of-life PV panel recycling industry. Fiscal incentives schemes can be created to encourage developers or owners to orienting houses for optimal interception of solar energy gain, and using appropriate roof materials to reduce the need for additional rooftop support structures for mounting of PV panels [96]. While this will increase chances of solar power generation from PV when installed, also improve affordability for rooftop PV. Study related to renewable energy integration in Nigeria [96] suggests that research on solar energy assessment should be better funded to be comprehensive in approach that requires participation of all relevant stakeholders.

#### 4.2 The Values and Hazards of End-of-life PV Panel

The construction of polycrystalline silicon solar cells which accounted for about 80% of solar PV panels in the market [97] can serve to illustrate the value and negative aspects of end-of-life PV panel in the context of Africa. While, monocrystalline solar modules have emerged as more efficient and gained significant market share in the recent years [98], the African continent still faces the challenge of dealing with polycrystalline PV waste from the older installations. The materials of value that can be recovered from polycrystalline silicon solar cells are Silver (Ag), Aluminium (Al), Copper (Cu), glass (as SiO<sub>2</sub>) and Silicon (Si). Other recoverable materials from the wider solar PV technology include Tellurium (Te), Indium (In) and Gallium (Ga) owing to their presence in thin-film cadmium telluride (CT) or copper indium gallium diselenide (CIGS) solar PV types [98]. For crystalline silicon panels, more than 85% of panel mass can be recovered on effective recovery of materials like glass (as SiO<sub>2</sub>), aluminium (Al), and copper (Cu) [94]. This recovery can be financially lucrative, especially for African countries as it has been reported [92] that a value of up to USD 450 million USD can be recovered from end-of-life panels by 2030 [92]. Such volume of recovery will be enough to produce 60 million new panels worth 18 GWp in capacity to be reused in the local markets. The same report also highlighted that positioning of Africa as the future reuse and value recovery centre of e-wastes will play a major role in the above-estimated markets for value recovery from end-of-life PV panels. Therefore, national policies to regulate and support this potential market should be developed ahead of time.

On the other hand, given the weak regulatory framework in Africa as discussed earlier, end-of-life PV panels are expected to end up in open dump sites where they will pollute water sources due to leaching into the ground and surface water with the toxic substances [99]. The contamination around the dump site can be carried far and wide by airborne contaminated dusts and ground/surface water. For example, some panels contain lead (Pb), which dissolves in acidic or alkaline environments, and are toxic to human and other organisms. Cadmium (Cd) from the PV panels could be potential source of toxic pollution to the environmental and human health [93, 98]. Lead (Pb) poisoning causes brain

and kidney damage along with other nuanced symptoms. Antimony, used as an additive to improve glass transitivity in the PV panels, eventually leaches into the surface water causing serious pollution. Another concern is incinerating end-of-life PV wastes at dump sites, which may occasionally be done to reduce accumulation over the time. However, doing so to solar panels releases toxic particulate matter from its polymeric components increasing health impact to local residence [100].

Despite the fact that volume of municipal solid waste is very small in Africa compared to the developed world, lack of appropriate waste management in most of the cities in the continent is already impacting human health and the environment [101]. Cost implication data of solid waste management (collection, transportation, disposal, recovery) in Africa is almost non-existent. Data from Malaysia indicate that 50% to 70% of the solid waste collection, transportation and disposal budget is normally spent in the collection phase only [102]. However, in most of the low-income countries, about 80-90% of waste management budget goes to collection alone with a collection success rate of about 47% of the generated waste [99], which is applicable to many African countries. With almost no budget for disposal, it is not unexpected that wastes are dumped openly in unoccupied lands and water channels [103]. Africa, being mostly consisting of low-income countries, the concern of e-waste hazards including end-of-life solar PV is a serious one which needs to be addressed from now.

#### 4.3 Sustainable PV Waste Management in Africa

Sustainable waste management is primarily based on the concept of 3R's: *reduce*, *reuse*, and *recycle* [104]. Regarding the end-of-life PV panels, the 'reduce' concept focuses on material reduction in production or substitution of the toxic materials with more benign materials. For example, there have been vigorous efforts by the industry and research to reduce glass usage in solar panels by improving its transitivity and design, and substituting the currently used non-recyclable polymeric thermosets with recyclable thermoplastic encapsulates (or elimination of need of encapsulation) [92]. Also, as mentioned earlier (Section 4.2), the solder materials traditionally used to be lead-based but currently are lead-free alloys.

The most challenging aspect of recycling is de-bonding the encapsulate material from the other materials. However, measures can be taken to reduce impurity and hence safeguarding the value of the recovered materials [105]. African countries should therefore emphasize on the related skills development programme in repairing, refurbishing, dismantling safety, and cannibalizing (for reusable spare parts) for the end-of-life or end-of-use PV panels amongst the African technicians. Promoting a sustainable path for cost effective recycling and reuse of end-of-life PV will potentially drive the growth of rooftop PV-based electrification and reduce the health and environmental concerns.

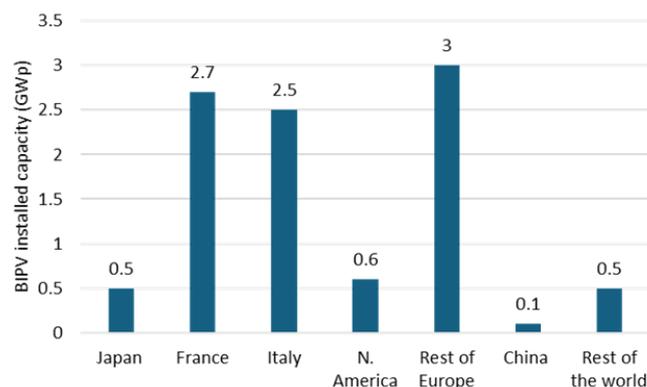
## 5. Building-integrated photovoltaics (BIPV) for Africa

### 5.1 Overview

Unlike the Building Adopted Photovoltaic (BAPV) panels, which are installed as an addition on the existing building envelop to generate electricity, Building Integrated Photovoltaic (BIPV) is used as integral building components, which act as both the building envelop and electricity generator [17]. Despite the potential of application to fight the global climate change, uses of BIPV has not grown as expected. Given the fact that the expected growth in BIPV has not been achieved as reported by Tabakovic et al. [106], the African continent is yet to adapt this technology at a scale (Table 4) and is estimated to have around 5% of the total BIPV installed capacity. More recent BIPV data [107] indicate that despite slow uptake, Europe, especially France and Italy have achieved significant growth as of 2019 (Figure 7). However,

**TABLE 4 GLOBAL BIPV INSTALLED CAPACITY IN 2014 AND ESTIMATED GROWTH [105,106]**

Region/country	BIPV installed capacity (MW)			
	2014	2016	2018	2020
Asia	443	1040	2115	3746
Europe	650	1141	2929	4838
USA	319	675	1200	1766
Canada	42	86	157	228
Rest of the world including Africa	81	184	355	561



**FIGURE 7 BIPV INSTALLED CAPACITY IN SELECTED REGIONS IN 2019 [107]**

### 5.2 Types of BIPV

There are many types of BIPV systems available in the market to be used as building roofs or facades [107,108]. However, these systems need to be further studied to adapt the most cost-effective and

technologically suitable option for the African market. Figure 5 illustrates some types of BIPV systems.



**FIGURE 5 - TYPES OF BIPV. ON ROOF SOLAR PANELS (LEFT), COMPLETE SOLAR ROOF (MIDDLE) AND SOLAR TILES (RIGHT) [109]**

BIPV systems can also be used in façades. For example, opaque solar panels can replace glass windows or BIPV material can form part of the curtain cladding or cladding of a building [110]. However, such systems are still novel and yet to see wide commercial roll-out. They won't be investigated further in this paper.

A complete Building Integrated Photovoltaic systems can be divided in three main technical components:

- a) **PV modules**, with specific characteristics developed for building integration, having appealing features (such as colour, texture, shape, surface finishing, and light materials) conceived for integration in existing buildings.
- b) **Mounting systems**, to mount the PV modules on the building envelope, such as on facades, roof, and external structures.
- c) **Energy systems**, which link the PV modules to the building, and the utility grid (if grid connected) to maximize the local use of the electricity generated, including storage, power conversion, power control, heating and cooling and e-mobility systems.

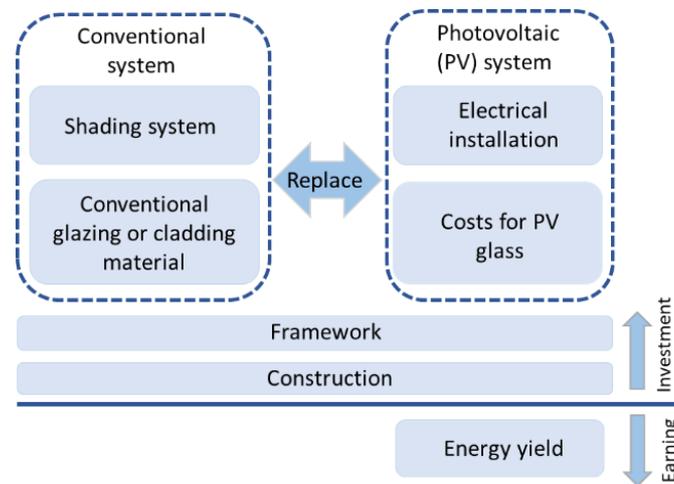
An example of a popular BIPV product is the Tesla solar roof tile [111] . The tiles are claimed to be stronger than traditional roof material and are design for easy installation. However, none of these products are known to be installed in the African continent.

### 5.3 Cost Benefits of BIPV

The building-integrated PV Panels can replace the functions of the usual building materials (e.g., cladding or roof tiles), meaning that any extra cost paid would be recovered through the electricity it generates over the years. Thus, BIPV can deliver a return on investment as shown in Figure 6.

BIPV can be utilised in new buildings in African countries by replacing traditional construction materials. The innovative concept of BIPV has gradually been adopted in some Western countries like Spain, UK [107, 110, 112], and Asian countries like India [16, 109, 113].

The benefits of BIPV indicate an untapped potential for the African continent. Therefore, it is very important that African countries adapt home grown solutions and policies to take advantage of BIPV [109]. One potential approach is to promote local manufacturing of BIPV solar materials at a scale, which could potentially lower product costs compared to imports by saving on shipping expenses. However, this approach will create job opportunities and local supply chain.



**FIGURE 6 ILLUSTRATIVE PRESENTATION OF ENERGY GENERATION AND EARNING FROM BUILDING INTEGRATED PHOTOVOLTAICS, AS A REPLACEMENT FOR CONVENTIONAL SYSTEM**

[114]

#### 5.4 Challenges of BIPV integration in Africa

The basic design of the BIPV solar system consists of an energy generating component (i.e., PV), energy conversion system (i.e., inverter or converter) and energy integration system to the building's electricity supply system [113,115–119]. The BIPV system can operate as an electrical supply system, making up the power supply on the grid [120]. If BIPV is used for a large building roof or façade, the key concerns in design and future implications could be, (i) complicated DC cabling, length of DC cables considering the size of the building, housing for panel strings/ combiners etc., (ii) access to any repairing or replacement if needed in the future, (iii) issues of trapped heat if used in façade, and (iv) scheduled replacement of components, especially panels/ tiles in the future.

Studies on the BIPV systems and their local integration in Africa are very limited, and they are yet to be widely deployed. However, some studies provided interesting insights into its potential. For example, a BIPV building was investigated in South Africa [46], which used rooftop tiles formed

from solar PV. It was reported by the authors that the BIPV system contributed almost 38% of the total cost of the building as the system served both the roles of protective roofing material and energy source. The proportion of the BIPV cost indicated in this report would have been comparatively lower by now as the solar PV cost decreased significantly since 2013. Although the system performed as intended, the elevated temperatures at noon resulted in a 20% decrease in performance of the BIPV. The study also reported that this heat contributes to increased indoor temperature, leading to more cooling demand. However, a good design of the rooftop structure can compensate these issues. For example, the roof with the BIPV can be designed so it faces north and tilts to the angle that produces the optimum solar photovoltaic output for that location. Also, the building should be designed to maximise natural ventilation to compensate for the increased indoor temperatures from the BIPV panels.

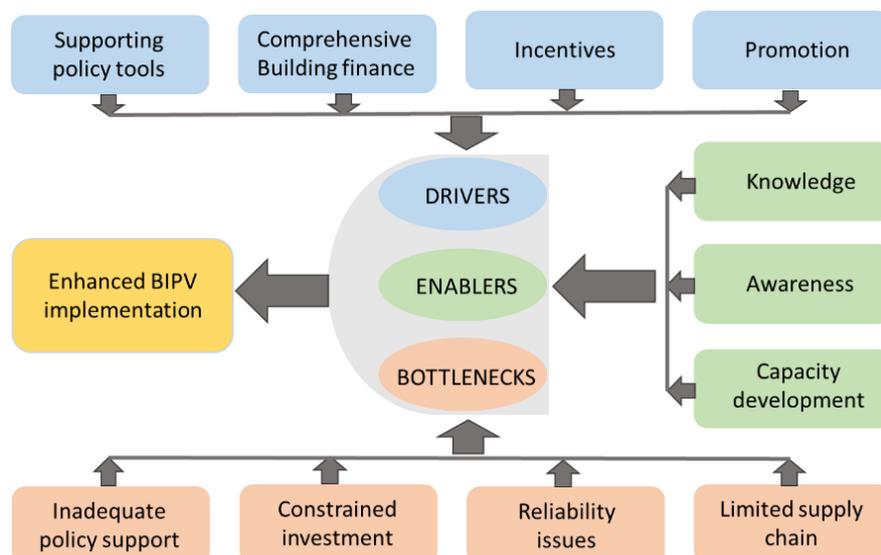
BIPV potential in Cameroon as reported in a study [36] notes that although many homes in Cameroon are huts or have simple steel roofs, there is an increase in modern villas being built. These villas represent a good opportunity for integrating BIPV. The authors also proposed that the thermal heat produced at the back of the BIPV material can be utilized for other uses around the house, such as for water heating or cooking. They suggest the opportunity for increasing BIPV in new builds in Africa with appropriate policies to enforce low energy buildings.

To further understand some of the major challenges moving forward with BIPV technologies in Africa at both national and regional levels, findings of the studies [109, 118] conducted in India can be adapted considering the similarities of the political, economic, and climate conditions between these two regions. The major bottlenecks and policy challenges of the BIPV system implementation in India which they suggested should be studied widely to better adapt this technology in Africa. These challenges around different areas are:

- (i) Policy
  - Lack of appropriate energy policy.
  - Low priority is given to BIPV in national planning, and weak policy implementation.
  - Lack of subsidies and benefits for BIPV (such as feed-in tariff arrangement).
  
- (ii) Technical
  - Lack of standardized technology.
  - Limited local manufacturing of specialized equipment.
  - Limited capacity in solar BIPV products to provide reliable power and efficiency.
  
- (iii) Economic

- Poor economies of scale, long payback period and high initial capital costs.
  - High installation cost at the user end.
  - Limited information on market potential.
- (iv) Human Resource
- Lack of technical experts and marketing professionals in BIPV sectors.
  - Limited in-house resource capacity for data gathering, analysis, and project management.
  - Lack of proficient Planning, commissioning, operation and maintenance of BIPV projects.
- (v) Information
- Lack of awareness creation in BIPV resource, technology, finance, market and supply.
  - Inadequate training and capacity building.
  - Insufficient information on BIPV policy.

Furthermore, it is clear from the studies [109, 113, 116] that to implement BIPV projects three key interconnected factors, (i) drivers, (ii) enablers, and (iii) bottlenecks are to be carefully considered for adaption in the African context as presented in Figure 7.



**FIGURE 7 – SCALING UP BIPV SYSTEM IMPLEMENTATION IN AFRICA (ADAPTED FROM [109,116])**

A potentially very important challenge that has not been given adequate attention is the security of PV installations from theft and vandalism [121]. Socioeconomic and political variables like lack of

employment and inequality are known to trigger the risk of theft and vandalism of not only public but private installations. Many cases illustrating such cause and effect situation in form of sabotage and theft of renewable energy infrastructure have been reported [122,123] Even though most of such reports are on utility-scale renewable energy projects, valuable residential renewable assets like rooftop PV and BIPV are not expected to be immune to burglary given that, for example, 62 - 81% of residents of a traditional Nigerian urban center experienced residential burglary within a studied six-month period [124]. Therefore, it should always be remembered that while renewable energy can create jobs in addition to other socioeconomic benefits as noted in [125], private and government collaboration is necessary to protect solar PV assets from the threat of insecurity. For example, private owners can deploy technologies like surveillance cameras. African governments can play roles for long-term security of solar PV assets through progressive improvement of social security and in the short-term by creating, through standard organizations, identification systems like barcodes, forensic markings and serial numbers to facilitate retrieval or rendering-worthless of stolen PV systems or components.

## 6. Discussion, Recommendations and Limitations

From the foregoing review, three aspects of solar PV were analysed in relation to Africa and are discussed in this section. The three areas can be grouped into timeliness, with rooftop solar PV seen as a present system that requires the most attention. Solar PV waste is an up and coming (near future, 10 to 30 years) problem that if not planned for now can become a major environmental issue. BIPV can be viewed as a system for the far future (over 30 years), but African countries will likely miss out on its benefits if not planned for now.

For rooftop solar PV many studies have shown its strong potential in African cities to provide reliable electricity supply whilst contributing extra power to national grids. The main reason being the high solar radiation these cities have. However, rooftop solar PV uptake in African cities is still lagging due to multi-faceted challenges as indicated in the PESTLE analyses above.

The political and legal aspects are very important to consider to help boost rooftop solar PV uptake. As the literature reveals, useful support from governments should be in the form of financial incentives. These can be in the form of reduced utility tariffs or payment for those exporting their electricity to the grid (feed-in tariff or net metering), tax exemptions and even grants to help with the solar PV purchases. From an economic perspective, many households, particularly in sub-Saharan Africa would struggle otherwise to afford such a system. Although many African countries have

introduced financial incentives and policies to boost rooftop solar PV uptake, some were not followed by effective support from governments resulting in poor uptakes. From the literature, a rare example of a successful program, was that of Ghana whose policy was to provide free solar panels, up to 500Wp, to households as long as they had energy efficient appliances installed, this was then complemented by a net metering programme. The Ghanaian government then set targets to monitor uptake, which they met. Technology leapfrogging by many fintech logy firms were also seen in literature as a way to boost affordability. These firms provide monthly purchase plans or rent-to-buy schemes for household unable to meet the high purchase price of solar PV rooftop system.

From social perspective rooftop solar PV can help maintain well-being by providing continuous clean electricity in line with the United Nations SDG goals (3, 7 and 11). This is particularly useful in sub-Saharan Africa where power cuts are a regular occurrence. Other benefits to society of rooftop solar PV uptake is job creation, this would help boost economies and further increase satisfaction and well-being among citizens (SDG 8). From a technical perspective, job creation will also boost the number of technicians in the field, meaning easier maintenance and faster installation times. Governments can support this through education programmes to raise awareness and by promoting companies that help train solar engineers and technicians.

Environmentally, the installation of rooftop solar PV systems is seen as a boost to nature and limiter of climate change (SDG 13). No greenhouse gas emissions take place during the operation of PV systems. Also, they offset the need for petrol or diesel generators meaning cleaner air and less noise in cities. However, in the near future when the solar PV systems are at their end of life, the potential for landfill waste from these systems can be significant. As revealed in the literature, solar PV waste is expected to increase multiple folds in the coming decades in African countries.

Solar PV waste is not only a landfill issue, but hazardous substances from some solar panels can cause pollution that can harm human health and wildlife. For example, lead and cadmium from some panels are toxic and if leached into the environment can cause poisoning. On the other hand, solar panels also contain some materials that are of great value once recovered. For example, silver (in low amounts), aluminium and silicon.

Some African countries have started drafting policies to consider solar PV waste. For example, Ghana has introduced an eco-levy (tax) on solar panels to account for waste collection. Kenya, Rwanda, Uganda and Nigeria have extended their e-waste policy to consider solar panel waste. However, in light of the current poor waste collection systems in most of sub-Saharan Africa the literature recommends specific waste treatment plants are built for solar panel waste urgently before it becomes unsustainable.

The future of rooftop solar PV in Africa can be BIPV as it has the strong potential of its dual benefit of being both a building material and power generator. However, BIPV installation in Africa is currently very low. Africa is estimated to have only around 5% of the total installed BIPV power in the world. The literature similarly had few research articles on BIPV applications in African countries. However, the benefits of BIPV is well documented across literature.

Most BIPV material is installed as roofing tiles or façade. One major assumed benefit from BIPV in Africa is the potential cost savings to developers and home-owners because of its dual functionality. However, further research is required to detail the long-term cost savings in Africa, in particular since many homes rely on cheap construction materials in the first place.

Several challenges were highlighted in literature in relation to BIPV potential. These need to be considered carefully and mitigated in order to realize the full benefit of BIPV. Some of these challenges are:

- BIPV materials installed in roofs can increase internal room temperatures.
- Complexity of internal electrical wiring of BIPV elements during construction
- Difficulty in carrying out maintenance and repairs once the BIPV materials are built in.

However, such challenges should not deter potential investors and governments in Africa from this renewable technology adaptation. Many innovative BIPV products are being produced to help reduce the above limitations. For example, the Tesla solar roof tile which is already being installed across North America, and is designed to be easily integrated into building roofs and replaced when required. However, such roof tiles are not yet known to have been installed in Africa.

Two studies of BIPV potential in Africa were found. The first in South Africa, which demonstrated the potential cost savings of using BIPV materials. Although the findings estimated a potential 20% decrease in solar energy output due to high temperatures accumulated in the BIPV material. The BIPV study in Cameroon indicated a potential for BIPV use in modern buildings and villas. Although many homeowners in the country may miss out due to the hut style housing they live in which is unsuitable for BIPV. Also, a BIPV study in India highlighted major bottlenecks to BIPV uptake include cost, technical resource (human and material) and lack of supportive policies Overall, the literature lacks research into BIPV technology in the African context with further research and development recommended.

Table 3 summaries a list of recommendations based on the literature analyses for standard rooftop PV, PV waste management and BIPV.

**TABLE 2 LIST OF RECOMMENDATIONS FOR SOLAR PV SYSTEMS IN AFRICA BASED ON THE REVIEWED LITERATURE**

<b>Area</b>	<b>Recommendation</b>	<b>Details</b>
<b>Rooftop Solar PV</b>	Government financial incentives	Affordability of rooftop solar PV should be increased through government incentives such as appropriate FiT, subsidies, tax relief, public-private partnership, grants, loans (low/zero-interest), and community loan sharing programmes.
<b>Rooftop Solar PV</b>	Improve Affordability through Fintech	Technology leapfrogging through the financial technology (Fintech) firms should be supported by the governments to help them facilitate payments for rooftop PV systems for end users (e.g., pay-as-you-go schemes, pay monthly, rent to buy). This would increase affordability for rooftop solar PV to the wider consumers.
<b>Rooftop Solar PV and BIPV</b>	Education and awareness campaigns	Climate education and literacy programmes should be promoted by governmental and non-governmental agencies. Solar energy awareness can be incorporated into the educational curriculum to encourage future generations in clean energy.
<b>Rooftop Solar PV and BIPV</b>	Skills training	Governments should support local companies/investors to develop solar energy skills in addition to supporting start-ups to engage in local manufacturing of solar technologies. This would develop indigenous technical skills as well as provide jobs.
<b>Solar PV and</b>	Solar specific waste	Governments should start planning for

<b>BIPV waste</b>	treatment plants.	end-of-life solar panel and BIPV recycling plants from now and provide appropriate training. This is in anticipation especially for the huge e-waste expected in the coming years from rooftop PV. The recycled material from these treatment plants can help drive jobs.
<b>BIPV</b>	BIPV for new build homes	New builds should be encouraged to consider BIPV at the design stage (e.g., as part of the roof or wall). Official standards and guidance can be produced to help designers, with particular attention made to optimum ventilation required for BIPV buildings in African climate context as well as the provision for easy repairs and maintenance.
<b>BIPV</b>	More BIPV research and development.	Further research and development of BIPV to be encouraged to help overcome the major bottlenecks highlighted in this study. Future research can also help guide government policies to incentivise its uptake and encourage developers into BIPV.

The limitations from this study are mostly related to BIPV potential in Africa. Due to the limited research in this field it's difficult to come to a definite conclusion on the potential of the technology. For rooftop solar PV, the literature is plenty, albeit some countries in sub-Saharan Africa lack research in this field. For example, Somalia, Chad, Niger, Malawi among others. For solar PV waste there is some research emerging in the field that indicate awareness of the growing problem in Africa.

## 7. Conclusion

The traditional power generation technologies and the use of fossil fuel-based resources in Africa need to be transformed to sustainable sources while increasing installed capacity to enhance socio-economic development of the continent. This work reviewed solar PV potential in Africa for three generational time-scales: present, near future and far future. For the present, the potential of wide scale rooftop solar PV systems was reviewed, particularly in African cities. For the near future, sustainable waste management of solar panels were considered in preparation for the vast e-wastes expected soon once the solar PV uptake increases (in the next 10 to 30 years). For the far future, BIPV in Africa and the challenges associated with this technology was investigated. As rooftop solar PV is already in use in Africa, the PESTLE (Political, Economic, Social, Technical, Legal, and Environmental) framework was considered to evaluate the current and expected impact in relation to these factors.

Scaling up application of rooftop solar PV in Africa still faces multi-faceted challenges as detailed earlier in the PESTLE analyses. African cities are not lacking solar resources but suffer from the deficit of technological capacity along with the limited financial and regulatory supports to utilise these.

African governments are required to introduce and drive an efficient mechanism through appropriate policies and enabling investment environment, so that the growth of the rooftop solar and BIPV sector can be facilitated. Such technology could serve in the cities and as well as in off-grid rural areas to provide energy for homes, offices, schools, hospitals, businesses, industries, etc while complementing the national grid. Government policies such as FiT and net metering to encourage uptake of these technologies have shown evidence of success, however, they need to be followed by strong implementation at a wider scale.

From a social and economic perspective, even with government supports, the initial cost of rooftop PV systems could be too much for most of the households in Africa. Private sector involvement allowing easier and affordable payment options for the end users can enhance dissemination. Successful financial methods may include 0% interest loan schemes (community loan) supported by non-profits or government institutions, as implemented in South Africa. This stresses the need for comprehensive public-private partnership.

A major challenge to the growing solar rooftop PV market is the e-waste disposal. End-of-life PV wastes are projected to rise rapidly in Africa with expected rising influx of rooftop solar PV. The level of preparedness of Africa to handle the mounting wastes as per the current status of policy framework and infrastructural development were assessed and found to be inadequate. African governments need

to develop appropriate regulations as well as start the building of solar waste treatment plants and create local capacities to handle these wastes sustainably in the future.

BIPV, with appropriate support as indicated above could be the future of sustainable homes in Africa. However, studies have shown that BIPV forming part of the roof material may increase indoor air temperature. This reduces comfort within the home and also decreases efficiency of the PV material. Based on the recent studies of BIPV in India, which is comparable in climate and social development to sub-Saharan Africa, the local BIPV dissemination perspectives should be sought to ensure success through taking into account all major factors (enablers, drivers and bottlenecks). Major bottlenecks are expected to be related to cost, technical resource (human and material) and lack of supportive policies. Therefore, supportive policies should be introduced, and incentives provided by Governments to developers and building owners to boost the uptake of this PV technology.

Supports in capacity building and financial flow from the international development partners and multilateral agencies are crucial for African countries in the acquisition of such PV energy technologies. This is so that it can achieve a decarbonised economy, particularly within the framework of sustainable development goals (SDGs). The use of such renewable energy technologies would reduce Africa's contribution to the global emissions, pollutions, climate change and global warming. Wide scale rooftop solar PV and BIPV can help Africa to surpass its goals of reduction in carbon emission by 2030 as per the Paris Agreement and COP 26 Glasgow reaffirmation.

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