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Vision and Reality: An Assessment of Saudi Arabia's In-Country Capacity to Deliver on Its Solar Ambitions

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Abstract

Saudi Arabia's 2030 Vision plans to install 40 GW of photovoltaic capacity in the country by 2030. This includes a requirement that deployed systems achieve a local content threshold of 33–35% for 2024–25, increasing to 40–45% for 2028 and beyond. With the exception of financing (75%), the level of local content for all other aspects of PV farms in Saudi Arabia is low (22–50%). In this paper, we consider the domestic manufacturing capacities of key components such as float glass, aluminum framing, steel, and concrete. Capacity constraints are evident, importing PV cells rather than modules (to increase local content by undertaking module lamination in the country) would require 58% of Saudi Arabia's float glass production from now until 2030. We estimate that 85% of modules will need to be manufactured in their entirety in country if the local content of all other aspects does not change. Such an approach could result in higher commodity prices in Saudi Arabia, certainly in the short term, leading to import sourcing and, in effect, worsening of local content of PV systems. Therefore, increasing local content across all aspects of PV systems is needed, with a focus on the local skills base and capacity.

Keywords: photovoltaics; Saudi Arabia; local content; supply chain

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1. Introduction

Saudi Arabia's electricity demand profile is dominated by residential demands (45% of electricity demand in 2022), of which 70% of this demand relates to air conditioning [1,2]. In 2023, 62% of electricity generation was from natural gas and 38% from oil. Wind and solar represented a very small contribution to electricity generation of less than 1%. Total electricity generation in 2023 was 453 TWh (note that this does include exports) [3].

Located within a region of high irradiance, there is a clear opportunity to utilize photovoltaics at scale in Saudi Arabia, with generation being broadly in phase with the electricity demand. Numerous studies have cited the potential of Saudi Arabia to become a renewables powerhouse, with excellent solar and wind resources [4–6]. Challenges remain, however, in relation to achieving such a vision, in particular relating to the low current electricity tariffs and the almost exclusive reliance on fossil fuels at present. The majority of the country receives high annual irradiance, and the photovoltaic power potential is estimated to be between 5.2 and 5.3 kWh/kWp per day across most of the country [7].

The Kingdom of Saudi Arabia (KSA) has a strong desire to diversify away from its reliance on oil and gas revenues in the long term. As of today, however, 50% of the GDP of

KSA is attributed to oil and gas production [8], ranking KSA first worldwide on this metric, followed by Qatar (40%), Kuwait (40%) and UAE (27%). In relation to diversification from fossil fuels, KSA has two key national solar photovoltaic (PV) targets for 2030. These are the following:

(i) To install 40 GW of PV capacity by 2030;
(ii) To install PV systems with a minimum local content level of 45% post 2028 [9].

The first target of 40 GW of installed PV capacity by 2030 can be achieved by financial investment supported by rapid planning approval policies, both of which are within the remit of the government. Worldwide, by the end of 2024, cumulative PV capacity exceeded 2 TW, with 600 GW of new PV systems being commissioned in that year [10]. The KSA 40 GW PV target has gradually evolved over the past decade and, in its current form, is a significant reduction compared to the initially stated target of 200 GW in the year 2018 [11,12]. By the end of 2024, the installed capacity of PV in KSA had risen to 4.3 GW [13], and there are numerous projects at various stages of the delivery pipeline (Ar Rass II 2 GW, Al Sadawi 2 GW and Saad II 1.12 GW) [14–16]. If the 2030 40 GW target is to be realized, an additional 35.7 GW of capacity would need to be installed over the next six years, corresponding to ~6 GW per annum if a yearly uniform installation rate is applied. This is clearly a very ambitious target, but one which could be achieved with strong policy support from the government.

The Public Investment Fund (PIF) is the main funding mechanism for large infrastructure development projects [17] in KSA. There is a strong desire to ensure that PIF-funded projects achieve the maximum possible benefit for the country rather than simply financially support external contractors and suppliers. This is assessed in terms of the metric 'local content' level, which is the percentage of a project cost that is spent locally within KSA. The PIF has stated that there is an aim to increase the local content in PIF flagship giga-projects and in their portfolio of companies to 60%.

In 2023, the global weighted average total installed cost of utility scale PV was USD 758/kWp, which is 86% lower than the 2010 value of USD 5310/kWp. This dramatic cost reduction has resulted in the levelized cost of energy (LCOE) of PV becoming cheaper than fossil fuel based generation in many countries. Approximately 50% of the cost reduction in PV is associated with the drop in module cost, driven predominantly by the economies of scale of mass manufacture in China [18]. In 2023 for example, China accounted for 85% of worldwide PV module production [19]. Saudi Arabia's utility scale PV CAPEX cost was approximately 5% higher than the global weighted average in 2023 at USD 794/kWp. The PV market in KSA is currently in a "take off" phase of deployment and is experiencing rapid growth. One would expect, therefore, that tender competition would start to bring down some of the non-module costs in KSA. It appears that the balance of the 40 GW target for KSA (35.7 GW) could be realized on the basis of additional headline investment of ~USD 28.5 billion, using the value of USD 794/kWp.

In 2023, KSA had a GDP of USD 1.07 trillion, so a PV investment of USD 28.5 billion would correspond to ~0.45% of annual GDP expenditure year on year for 6 years [20]. Provisional figures for GDP in 2024 from KSA's General Authority of Statistics indicate that the Saudi economy grew by a further 1.3% in 2024 [21]. Whilst this installation rate and cost seem reasonable, it is not immediately clear whether this approach would be compliant with KSA's stated local content targets. The focus of this paper is not therefore on the financial affordability of the 40 GW policy, which we deem as affordable in a KSA context, but rather on whether this is realistic in terms of the timeframe and local content target. IRENA reports that in Saudi Arabia in 2023, the LCOE increased by 18% from the previous year to reach USD 0.044/kWh, after decreasing 31% during 2022. However, the LCOE in 2023 was still lower than in 2021, when it was USD 0.053/kWh [18]. In comparison, the

LCOE for gas-fired power plants in KSA was estimated by Hayat et al. to be in the range of USD 0.023–0.062/kWh [22]. This range is for gas prices between USD 2 and 8 per MMBtu and assumes a capacity utilization factor of 85% for a CCGT power station. Recent power purchase agreements for new CCGT gas power stations in KSA (Rumah 1 and 2, Nairiyah 1 and 2) have been in the range of USD 0.045–0.046/kWh. A 2000 MW PV plant contract (Al-Sadawi) was also recently signed at USD 0.013/kWh [23]. These figures highlight that PV in KSA has already crossed the economic crossover with fossil fuel power generation even when accounting for the intermittent nature of PV generation. This paper, therefore, considers that the economic case for PV at scale in KSA has already been made.

Local content (as defined by financial value) is a key driver of KSA energy policy. In the context of grid-connected PV systems, there are clear differences in the level of local content across four categories: (i) module and inverters, (ii) balance of system hardware, (iii) installation, and (iv) soft costs. The stated KSA local content target post 2028 for large-scale PV is 45%. Prior to 2010, achieving a 45% local content level for a large-scale PV farm for a country without significant in-country manufacturing of cells or lamination would not have been possible. In 2009, for example, the global weighted average of utility scale solar PV costs was around 60%, associated with module and inverter costs [24].

Here, we analyze the recent growth of PV installations in KSA and their level of local content to estimate under what conditions the 2030 local content could be achieved. We follow the latest KSA guidance for local content estimation [25] alongside exploring the potential impact of higher levels of local content through a number of scenarios such as increasing local skills capacity in system design.

Large-scale solar is a rapidly growing market in KSA with solar-powered electricity generation expected to reach 1.01 TWh in 2025. The annual growth rate for solar in KSA 2025–2029 is expected to be ~14% [26]. Freestanding PV systems (optimized slope and azimuth) in KSA have an estimated annual yield of 1831 kWh/kWp according to PV-GIS [27]. The 40 GW target of PV capacity would therefore generate around 73 TWh per annum, representing around 20% of the country's electricity demand in 2030 [28].

2. Materials and Methods

In this paper, we will address the cost reduction trend in large-scale PV systems in KSA by aspect (module, inverter, installation, etc.). This will enable the study to determine the level of local content (LC) by aspect, which will be required to meet the KSA targets.

2.1. PV System Component Cost Projections

The International Renewable Energy Agency (IRENA) has published an annual breakdown of KSA large-scale PV system costs since 2018 [18,29–33], which we have normalized here to the 2023 value of the costs in USD. IRENA's costing methodology involves collecting and reporting cost and performance data from a global database of renewable power generation projects. IRENA state that they estimate costs from the perspective of private investors, whether they are a state-owned electricity generation utility, an independent power producer (IPP), or an individual or community looking to invest in small-scale renewables. The analysis excludes the impact of government incentives or subsidies, system balancing costs associated with variable renewables, and any system-wide cost-savings from the merit order effect. The cost analysis does not take into account any CO_2 pricing or the benefits that renewables may have in reducing other externalities such as reduced local air pollution. The benefits of renewables being insulated from volatile fossil fuel prices are also not considered in their analysis. IRENA compile data from a variety of sources, such as IRENA Renewable Costing Alliance members, business journals, industry associations, consultancies, governments, auctions, and tenders. Data are collated into a single repository—the IRENA Renewable Cost Database (which holds information on ~21,000 projects). The Renewable Cost Database includes a mix of confidential and public domain data, which are used to generate the costings used in this paper. See Renewable power generation costs in 2023, ANNEX 1: Cost Metric Methodology for further information [18].

In addition, IRENA has for some years collected cost data on a consistent basis at a detailed level for a selection of PV markets, which includes KSA. In addition to tracking average module and inverter costs, the BoS costs are broken down into three broad categories: non-module and inverter hardware, installation costs, and soft costs. These three categories are composed of more detailed sub-categories, which can give greater understanding of the drivers of solar PV BoS costs and are the basis for the analysis presented in this paper. Further detail on the BoS hardware, installation, and soft costs is given in "Table A2 BoS cost breakdown categories for solar" of renewable power generation costs in 2023 [18].

Estimates for KSA's material usage data relevant to PV module production (such as glass, aluminum, plastics, and copper) and PV farm installations (such as steel and concrete) come from a number of sources. Statista is the most commonly used source in the paper. Statista states that it collects data from a wide array of sources (>22,500), both public and private, including established statistical offices, industry and trade associations, public institutions, specialized research companies, and financial data providers. In addition to these secondary data, Statista also conducts its own primary research through surveys and analyses, offering exclusive data not available elsewhere.

Figure 1 shows that, as would be expected, the PV module cost is a major cost in KSA, representing 25% of the overall cost in 2018, rising to 30% in 2023. This increase is perhaps somewhat counterintuitive, as for most countries, the module cost contribution has dropped during this period. This apparent anomaly in a KSA context reflects the very high reported margin costs in particular in KSA between 2018 and 2020. The overall cost per kWp in KSA has dropped by 48% over this period from USD 1533 to 794/kWp. An exponential decay fit has been applied to this overall cost. The fit is as follows:

KSA PV farm cost (USD/kWp) in year n (year 1 = 2018, year 13 = 2030) = 1719.3 EXP (-0.145 n), R2 = 0.89.

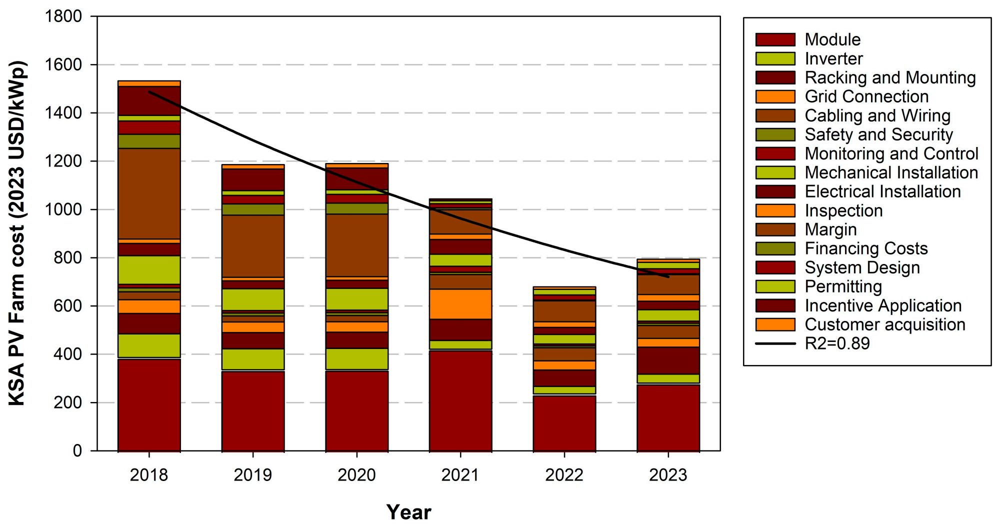
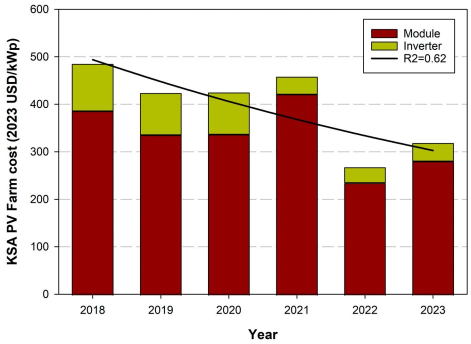


Figure 1. KSA currency 2023 USD/kWp large-scale PV farm costs. 2018–2023, adapted from IRENA annual reports [18,29–33]. An exponential decay fit to the overall cost is shown. PV farm cost in year n (year 1 = 2018, year 6 = 2023) = 1719.3 EXP (-0.145 n), R2 = 0.89.

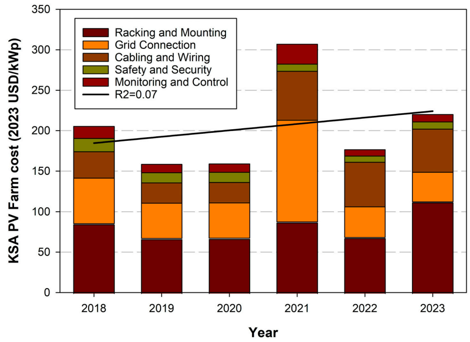
IRENA consider a PV system in terms of sixteen different aspects across four categories as follows:

1. modules and inverters: (1) module (2) inverter.
2. BoS hardware: (3) racking and mounting, (4) grid connection, (5) cabling and wiring, (6) safety and security, (7) monitoring and control.
3. installation: (8) mechanical installation, (9) electrical installation, (10) inspection.
4. soft costs: (11) margin, (12) financing costs, (13) system design, (14) permitting, (15) incentive application, (16) customer acquisition.

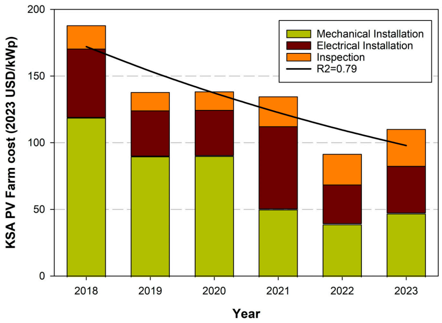
If we look at the four IRENA categories separately, as shown in Figure 2, we have applied an exponential decay fit for module and inverters, installation, and soft costs. A linear fit has been used for the BoS costs, but this is essentially a weak trend. Soft costs (d in Figure 2) have shown a significant reduction between 2018 and 2023 with margin and incentive application showing a step change reduction post 2020. We have therefore chosen to estimate the cost reduction profile for soft costs to 2030 by using the 2021–2023 data only to create a cost projection up to 2040.



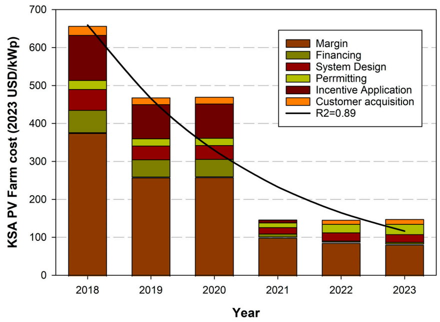
(**a**) KSA module and inverter costs in large-scale PV systems, 2018–2023, from IRENA cost reports



(**b**) KSA balance of system (BoS) hardware costs in large-scale PV systems, 2018–2023, from IRENA cost reports



(**c**) KSA installation costs in large-scale PV systems, 2018–2023, from IRENA cost reports



(**d**) KSA soft costs in large-scale PV systems, 2018–2023, from IRENA cost reports

Figure 2. IRENA large-scale PV system costs, 2018–2023 (currency 2023 USD/kWp), from IRENA cost reports [18,29–33]. (**a**) Module and inverter costs; (**b**) balance of system hardware costs; (**c**) installation costs; (**d**) soft costs.

2.2. Local Content Assessment

In KSA, the Local Content and Government Procurement Authority (LCGPA) provide a local content accounting tool for projects in the Kingdom. We have used the Local Content Score Template (vn 7, 21 March 2025) [25] to assess local content between 2018 and 2030.

Margin (profit) is defined as a separate financial category by IRENA, whereas in LCGPA's local content analysis, margin is incorporated into each aspect of the project. Here, we deem the local content value of margin in a specific year to be the same as that calculated for a KSA PV system using the LCGPA metrics. In this way, we assume that margin is associated pro rata across all PV system costs and so would not influence the overall local content estimate; i.e., if the PV modules cost 25% of the overall USD/kWp cost of the system, we have assumed that 25% of the margin value would be associated with PV modules. This assumption would not hold true if margin was disproportionately associated with a small number of aspects such as financing, which have a high local content value. Since margin was the second highest individual cost of a KSA PV system between 2018 and 2020, behind only the module cost, this scenario of disproportionate distribution does not appear to be the case here, which justifies this approach.

The LCGPA currently assigns local content for PV modules at 22%. This value includes not just the PV module manufacture costs but also the transport, distribution, and reselling costs. At present, in KSA, the local content level for PV module manufacturing is very low. The 2024 KSA PV module manufacturing capacity, for example, is ~1600 MWp. Lamination costs correspond to around 50% of the overall module cost, so 1600 MWp of lamination is considered equivalent to local content of 800 MWp of module manufacture (cell and lamination). In 2024, KSA added ~3700 MWp of PV, of which 800 MWp can be considered as manufactured local content, which corresponds to 22%; interestingly, this is the same as the LCGPA value (Table 1). This forms the basis of Scenario S1, which represents the "Business as Usual" (BaU) case in this paper.

Table 1. KSA Local Content and Government Procurement Authority (LCGPA) [25], local content level for aspects of a large-scale PV farm.

Sector	Description	Local Content (%)
Labor	Saudi employees	100
costs	Foreign employees	37
Services	KSA industrial services (testing, certification . . .)	30
	KSA local professional services (engineering consulting, accountancy)	50
	KSA local representative of foreign professional provider	20
	KSA construction, specialized construction activities for buildings and civil engineering works	35
	KSA finance and insurance	75
	KSA transport and logistics	40
	KSA cement and gypsum, locally produced cement, concrete and gypsum	50
	KSA steel rebar manufacturing	60
	KSA other manufacturing (includes PV modules and inverters)	22

2.3. Domestic Capacity to Supply PV System Components

The cost of a PV module can essentially be considered as the cell cost and the overall module cost (lamination, wiring, frame, etc.). Here, we assume that solar cell production costs represent 50% of a module cost, which is a typical value [34]. As stated previously, KSA already has a limited cell manufacture and module lamination capacity domestically, which can be used to support the local content level. Table 2 shows the current KSA solar PV module manufacturing capacity and stated planned new capacity. We use these data as the basis for additional modelling scenarios. Scenario S2 corresponds to 4300 MW PV lamination capacity per annum, whilst Scenarios S3 to S6 are justified on the basis of a future planned capacity of up to 30,000 MW/year of cells and modules (Table 2).

Table 2. KSA solar PV module current and potential manufacturing capacity per year and modelling scenarios.

Manufacturer	2019	2022	2023	2024	2025	Unspecified (S3 to S6)
Solar PV cell and module manufacturing plant (cells and modules)	100	100	100	100	100	
Masdar Solar Panel Factory "Masdar Solar" (module assembly)		150	450	1200	1200	
Desert Technologies Industries (module assembly)	110	100	300	300	3000	
RELC, Jinko Solar and Vision Industries (cells and modules)						10,000
RELC, LUMTECH holding and Vision Industries (ingot and wafers)						20,000
Total	210	350	850	1600	4300	30,000

If the stated Masdar Solar and Desert Technologies Industries lamination facilities highlighted in Table 2 were to achieve their stated capacity growth, then the lamination capacity would reach 4300 MW/year by 2025 (equivalent to 2150 MW of local content). This would mean that the local content for PV would rise to 36% (local content = 2150 MW/6000 MW required per year) (S2). Scenario S3 considers 100% in-country lamination (50% local content for PV).

Domestic lamination and/or cell manufacture will, however, require the in-country manufacturing capacity of other components (glass, aluminum framing, etc.) for the module fabrication to be considered as local content. Here, we look at these supporting industries to assess their capacity to support KSA's solar ambitions. Material usage (by weight) for a large PV farm in KSA with concrete foundations is shown in Figure 3. These material flows have implications for LC levels as the manufacturing capacity will essentially be inelastic in most cases (such as glass) and so increased demand may result in higher prices. This may result in suppliers choosing to import these materials to lower costs, which will, in turn, dilute the local content level of PV systems in KSA.

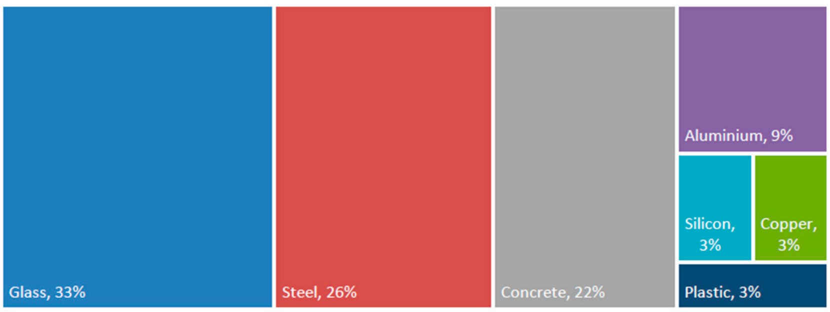


Figure 3. Usage of core materials by % weight for a PV farm in KSA [35].

3. Results

We assign the local content values from Table 1 to the extrapolated cost projections (Figure 1) to establish our Business-as-Usual scenario (S1: BaU) of local content to 2030, as shown in Figure 4.

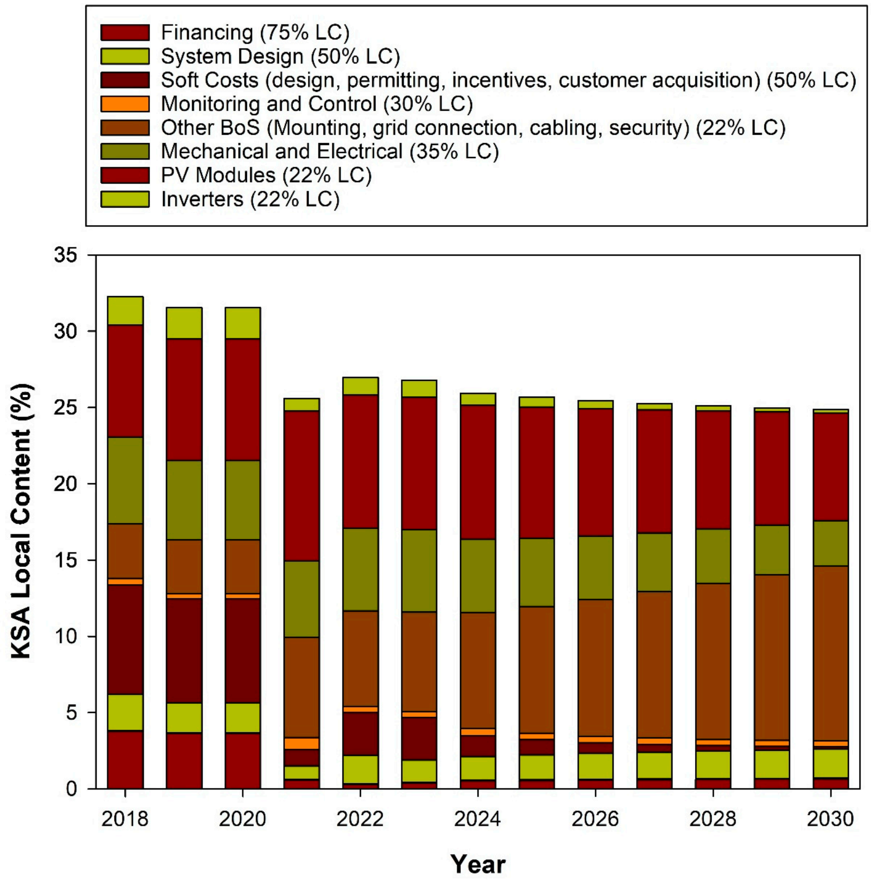


Figure 4. S1 BaU: KSA PV farm local content (%) from 2018 to 2030 based on LCGPA local content percentages and cost projections based on IRENA KSA data.

It is interesting to consider whether the high margin and soft costs between 2018 and 2020 create the relatively high initial local content projection values for this period. There are several possible reasons for the high margin and soft costs between 2018 and 2020. Saudi Arabia is currently transitioning to a consolidated market dominated by a few major players. These currently include, in no particular order, Alfanar Group, Abu Dhabi Future Energy Company (Masdar), EDF Renewables, Saudi Electricity Company, and ACWA Power. We believe, therefore, that prior to this consolidation, high margin and incentive application costs may have been due to the following:

(i) The presence of strong government support to encourage acceleration of investment in the country in PV at a point in market development where it was less consolidated;
(ii) The possibility that the tapering of incentives did not keep pace with the global reduction in the cost of PV during this period;
(iii) The initialization of localization of the KSA PV supply chain reducing costs.

We have therefore taken the margin and incentive application cost between 2021 and 2023 only to provide a projection curve that better reflects the more competitive market conditions that exist in KSA today. The 2030 target is 45% local content, while the BaU projection to 2030 is projected to achieve only 25% local content based on LCGPA 2025 values. The authors acknowledge that these values will of course change as local content levels improve, but it is clear that the 2030 target of 45% appears challenging at present.

If KSA were to undertake a significant level of either PV lamination (of imported PV cells) or PV cell manufacture domestically, this would clearly improve the local content level. This approach does, however, have the potential to create disruption to material supply chains in the country, as outlined above. China currently dominates global PV supply chains with over 80% market share across all manufacturing stages of solar module manufacture (such as polysilicon, ingots, wafers, cells, and modules) [36]. If we consider the 40 GW by 2030 KSA target, we see that this could have material constraint implications for glass, concrete, and copper. For example, as shown in Table 3, if all PV modules were to be laminated in KSA (S3), 58% of KSA's current annual glazing production would be needed. Such a level would clearly result in unit cost rises for glass in KSA unless additional production could be brought on stream, which is a significant undertaking in the short timeframe required.

Table 3. Assessment of material requirements for the KSA 40 GW PV target [33] and percentage of KSA in-country production. Data sources: glass [37], steel [38], concrete [39,40], aluminum [41], silicon [42,43], copper [44], plastic [45].

Material	Percentage by Weight (%)	Weight for 40 GW PV (tonnes)	Yearly Demand (tonnes)	KSA in-Country Yearly Production (tonnes)	Production Year Data	% of Yearly Production
Glass	33	2,800,000	467,000	803,000	2018	58
Steel	26	2,240,000	373,000	8,700,000	2021	4
Concrete	22	1,880,000	313,000	550,000	2021	57
Aluminum	9	760,000	127,000	999,000	2020	13
Silicon	3	280,000	47,000	593,000	2018	8
Copper	3	280,000	47,000	75,000	2020	62
Plastic	3	240,000	40,000	13,550,000	2016	0.3
Total	100	8,480,000	1,413,000	26,077,000		

The potential concrete production in Table 3 is estimated based on the yearly cement production in KSA, which is 55,000 tonnes [39], and the ratio of cement to concrete in foundations, which is 1 part cement to produce 10 parts concrete [40]. The other parts in the concrete mix are sand and aggregates, which can be regionally sourced with a negligible impact on the supply. Foundations are mixed 1 part cement to 3 parts sand to 6 parts aggregate. Hence, 57% of KSA's current annual cement production would be needed, which is likely to create shortages and cost increases unless additional production could be brought on stream quickly to achieve the target.

Table 3 also shows the potential silicon production based on current silica production in KSA. 1,400,000 tonnes is the annual production of silica sand in KSA [42], which can be heated and blended with a carbon source to make silicon [46]. Silicon production from silica sand is possible and could be beneficial in KSA as two samples from two different deserts in KSA contained 39.4% and 45.3% silicon [43]. Using the average of 42.4%, the potential silicon production was estimated to be 593,250 tonnes of silicon per year if KSA decided to intensify in-country silicon production. However, this scenario is purely based on an abundance of raw materials, and the chemical characteristics of the silica sand in the region and is not based on technical, financial, or economic feasibility.

Figure 5 shows seven modelled deployment scenarios (S1 to S7) to 2030 for PV in KSA, each installing 6000 MWp per year to deliver the 40 GWp target for 2030, as follows:

- S1: BaU assuming PV modules and inverters at 22% LC level from LCGPA.
- S2: 58% in-country lamination capacity, 2 new plants, equivalent to 29% LC level.
- S3: 100% in-country lamination capacity, equivalent to 50% LC level.
- S4: 75% local content for PV modules (cell manufacture and module lamination).
- S5: 85% local content for PV modules (cell manufacture and module lamination).
- S6: 100% local content for PV modules (cell manufacture and module lamination).
- S7: 79% local content for PV modules (cell manufacture and module lamination), 90% LC for financing, system design, soft costs.

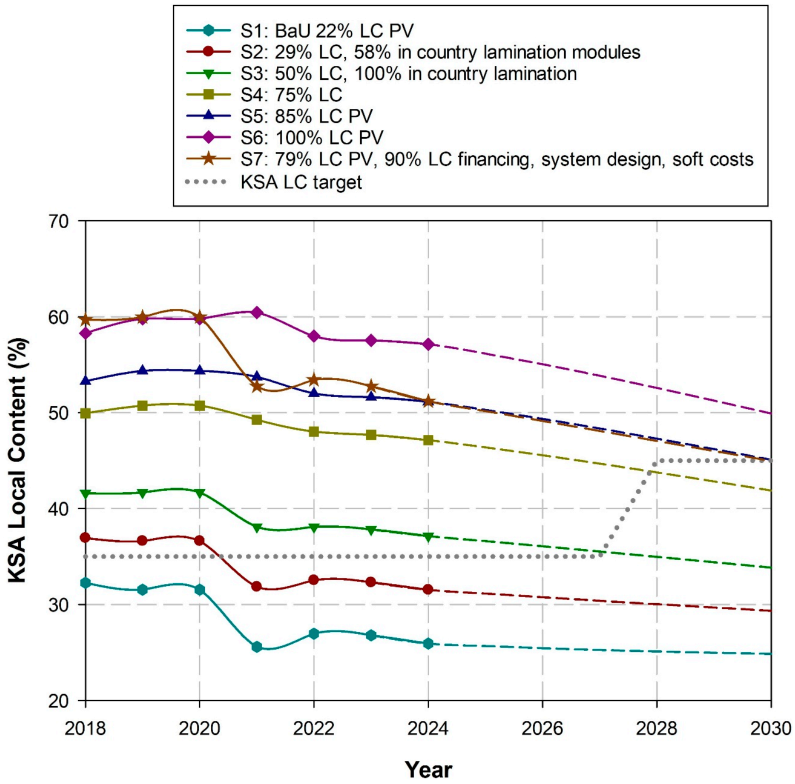


Figure 5. Seven scenarios for KSA PV farm local content (%) from 2018 to 2030 based on LCGPA local content (LC) percentages and cost projections based on IRENA KSA data. S1: BaU assuming PV modules at 22% LC level from LCGPA; S2: 58% in-country lamination capacity as of 2024, effective 29% LC level; S3: 100% in-country lamination capacity, equivalent to 50% LC level; S4: 75% LC for PV modules; S5: 85% LC for PV modules; S6: 100% LC for PV modules; S7: 79% LC for PV modules, 90% LC for financing, system design, soft costs.

The dotted grey line in Figure 5 shows the KSA local content target. Achieving the 45% local content target by 2030 (if the LCGPA local content values remain unchanged apart from PV modules) will require 85% of the PV modules to be manufactured domestically (S5 in Figure 5). This is a fundamental shift from where we are today (about 29% local content for PV modules, S2). There are announced plans for KSA to realize the entire in-country cell and lamination, but the timeframe for this is currently unclear.

It is also interesting to consider the LC level change if the focus was not on the PV modules but on the other aspects of the PV system. At present, financing is considered by LCGPA as 75% LC, with all other aspects between 22 and 50%. Scenario S1 BaU is projected to achieve 25% LC in 2030. If the skilled sectors classified under soft costs by IRENA (aspects 11 to 16) were all to achieve 75% LC by 2030, S1 would increase to 26% LC. If the semi-skilled installation sector (mechanical, electrical, inspection) were to similarly increase to 75% alongside 75% LC for soft costs, the LC for Scenario S1 BaU in this case would be 29%. If the balance of system hardware were to achieve 52% LC, then the overall LC of PV systems is estimated to be 45% with the LC of modules and inverters both remaining unchanged at the current level of 22%.

4. Discussion

The National Industrial Development and Logistics Program (NIDLP) of KSA has four key focus sectors—logistics, industry, mining, and energy—alongside two priority areas of the fourth industrial revolution (AI, IoT, etc.) and local content [47]. The mining sector is envisaged to provide key minerals for the renewable energy industries, notably feedstock for polysilicon production, alongside raw materials such as iron, copper, and aluminum. In parallel, KSA has been investing heavily in its transport network and undertaking infrastructure upgrades to ensure supply chain resilience for the country. The National Industrial Development and Logistics Program and National Transport and Logistics Strategy (NTLS) in KSA are targeting 10% GDP contribution from logistics by 2030 [48]. The plans include an investment of USD 133.3 billion to develop essential infrastructure in airports, railways, and ports to strengthen supply chain resilience. This approach will maximize local, regional, and international connectivity. Whilst enhancing international connectivity is a clear, logical strategy, it could potentially be seen as negative for the local content aspirations for solar in KSA if it makes it easier (and therefore cheaper) to import PV cells and modules.

Alnemeiri et al. present an exhaustive review of the literature relating to the impacts of Saudi Arabia's energy diversification strategy [49]. They highlight the complex interplay between the management of oil and gas reserves (and the associated revenues on international markets) without neglecting institutional quality, governance, and the interaction between the business models of state-owned companies in the energy sector. They note that "creating well-defined and consistent policies and regulations can foster a reliable environment for investors". This has not been the case in recent years in KSA in relation to PV targets in particular.

Silicon PV module lifetimes have increased from around 15 years in the 1990s to between 32 and 35 years currently [50]. The point at which PV arrays will be upgraded/replaced is dependent on several factors beyond simply the degradation of the array over time [51]. For example, if a location was to have a constrained power network, this may strengthen the case to upgrade a PV farm in that location; if applied with battery storage, it could provide grid support. Countries are now beginning to appreciate that there will become a significant in-country recycling challenge related to PV over the next decade. In a KSA context, this will offer the opportunity for the establishment of an in-country circular economy approach [52] for this sector, which should support the local content aspirations discussed here. Islam et al. have explored this issue in a KSA context to 2043, assessing the capacity, number, and location of recycling plants that will be required [53].

Solangi et al. have also evaluated the challenges of the Saudi 2030 vision in relation to the circular economy. They note that there is a strong need to develop education and training programs to develop a competent workforce driving sustainable energy use and the green economy. Their study highlights cause and effect challenges linked to this study and focuses on local content and potential spillover effects. They note that the lack of a skilled workforce and social resistance are as important to address as the high investment costs and limited regulatory support for renewables [54]. Solangi et al.'s call to deliver a skilled workforce is echoed by Alyousif et al., who mapped KSA's transition to 2060, stating that "The success of these structural changes' hinges on significant investment in capacity building. Enhancing the technical skills and capabilities of local industries and workforce is essential for supporting the implementation and scaling of low-carbon technologies" [55]. Similarly, Islam et al. highlight that the minor share of renewables in the current energy mix requires education and training for both the skilled and semi-skilled workforce [56]. All these highlighted skills and training gaps are directly linked to the local content challenge of PV systems in a KSA context, where it is important to not focus purely on the PV cell or module. Enhancing local content across all sixteen of IRENA's aspects of a PV system in KSA is required.

Apeaning et al. have evaluated the impact of early energy transition initiatives on the policy costs of achieving the Kingdom's net-zero target. They suggest that compared to a delayed implementation scenario, early action reduces long-term policy costs by 38–72%

over the period from 2025 to 2060, driven by accelerated energy system transformation. This study reaffirms the critical role of Saudi Arabia's energy price reform in reducing primary energy consumption and GHG [57], which will further support the transition to renewables by widening the LCOE between renewable and fossil fuel generation in KSA.

Local content targets in a KSA context have been in place for several years. However, there has been limited attention paid to the direction of the trend in local content projections in a KSA context. This challenge is exacerbated by the development phase of PV in KSA, which has only recently entered a full commercial basis. This is evidenced by the high percentage cost of margin, financing, and incentives for PV systems in KSA between 2018 and 2020. Such a level of cost analysis is possible as a result of IRENA's annual reporting of the cost breakdown of PV systems in a KSA context since 2018 [18,29–33]. If, as estimated here, it is the case that 85% of PV supply will be required to be via in-country module production to realize KSA's local content target, then major challenges will clearly arise. Such a change would result in significant stress to in-country supply chains in KSA, in relation to glass, concrete, and copper in particular. Such production would divert approximately 49% of KSA's glazing production, 48% of concrete (for mounting), and 53% of copper (Table 3). It is clearly unrealistic to divert such a high percentage without creating severe market disruption. The increase in demand for these materials would increase in cost, and it is likely that the local content level would be reduced due to the need for imports. KSA's strategy of enhancing its trade connectivity through NIDLP investment increases this risk.

The policy and energy landscape in KSA has, however, been quite volatile in recent years with not only a scaling back of renewable targets but nationally significant disruptor policies being actioned, including NEOM, Qiddiya, and Red Sea Global [58]. NEOM is a planned city being built in the Tabuk Province in the northwestern corner of KSA, due east of Egypt across the Gulf of Aqaba and south of Jordan. The total planned area of NEOM is 26,500 km^2 and includes THE LINE, a smart city in NEOM to be housed in a very long single building (170 km long, 500 m high, and 300 m wide). Qiddiya is a planned entertainment and tourism megaproject in Riyadh, including a motor racing circuit and theme parks. Red Sea Global is a tourism destination project on the Red Sea coast of KSA in Tabuk Province. The project aims to have 50 hotels with more than 8000 rooms on completion across 22 islands and 6 inland sites.

NEOM has the potential to divert significant resources and demand for key materials (such as glazing) but also change the investment landscape for PV in KSA, which may result in additional in-country supply capacity. These new developments may lead to an acceleration of investment, which will benefit the 40 GW target, which is assessed here. The true scale and timeframe of NEOM is, however, difficult to assess at present due to a number of recent announcements in relation to this project and its timeframe [59].

5. Conclusions

The reason why the local content target appears so challenging to achieve is that not a single aspect of a PV system in KSA is considered to be 100% local content at present. As shown in Figure 4, using the BaU scenario (S1) for cost projections of PV modules, the local content level reaches around 25% by 2030. Only financing has a local content level above 50% at present in the LCGPA analysis. This makes it really challenging to achieve an overall local content level of 45% even if all the PV modules are manufactured domestically (S3).

We estimate that 85% of PV modules would have to be 100% local content to achieve the 45% KSA target (S5), which is a dramatic change from where we are today. This level of in-country manufacturing would put stress on key in-country supply chains, most notably glass and concrete, which would probably result in spill-over effects of the import of these materials, and so the actual local content level would then probably fall below 45%. In the longer term, additional in-country manufacturing could of course be brought on stream to meet this increased demand, but this is not possible to adhere to KSA's 2030 timeline.

If the financing, system design, monitoring, and control aspects of PV farms could be increased to 90% local content, this would reduce the percentage of PV modules, which would need to have 100% local content by 2030 to 79%. This will require the enhancement of the skills base in KSA, which numerous studies highlight as a key issue for KSA. If we were to factor in the spill-over effects to other industries, this suggests that it is probably better to invest in skills capacity in these aspects rather than by purely trying to maximize the in-county PV capacity to achieve the 45% target. In addition, if PV cell prices were to drop more aggressively than projected here, due to further cell innovation, for example, local content targets are unlikely to be realized. In this scenario, the local content estimate would be even more sensitive to the balance of system costs, which are currently predominantly outside of KSA.

It is clear that for local content aspirations to be met, both in the short, medium, and long term, there is a need for KSA to look beyond in-country module manufacturing. This approach could result in higher commodity prices in Saudi Arabia, certainly in the short term, resulting in import sourcing and, in effect, worsening of the local content of PV systems. Local content across all aspects of PV systems needs to be enhanced. Aside from financing, this indicates that there needs to be a focus in KSA on investing in the development of the local skills base and capacity at both the skilled and semi-skilled level. Skilled and semi-skilled capacity needs to be addressed concerning "installation" and "soft costs" aspects of systems in particular.

Actionable policy measures could include the introduction of specific local content requirements for sub components of PV projects (which gradually tighten over time). This would require developers to invest in training and local capacity to enable them to bid for publicly funded projects in KSA going forward. This would be alongside support for education/skills training centers in these key sectors. This is highlighted by changes to Scenario 1BaU, where, if KSA were to achieve 75% LC across soft costs and installation (both of which are determined by in-country skills capacity), the LC by 2030 would rise from 25% to 29%. In this case, if the balance of system hardware were to achieve 52% LC, then the overall LC of PV systems in 2030 is estimated to be 45%, with the LC of modules and inverters both remaining unchanged at the current level of 22%.

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Abbreviations

The following abbreviations are used in this manuscript:

BoS	Balance of System
GDP	Gross Domestic Product
IRENA	International Renewable Energy Agency
KSA	Kingdom Saudi Arabia
LC	Local Content
LCGPA	Local Content and Government Procurement Authority
LCOE	Levelized Cost of Energy
NIDLP	National Industrial Development and Logistics Program
NTLS	National Transport and Logistics Strategy
PIF	Public Investment Fund

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