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Solar photovoltaic manufacturing in Africa

Opportunity or mirage?

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Solar photovoltaic (PV) technology is a key clean energy technology and an important source of clean electricity critical for the global green transition. Based on data on critical minerals and trade, we explore critical questions: how can Africa leverage its natural resource endowments, trade, and latent productive capabilities for solar PV manufacturing, and what are the opportunities for regional integration and strategy? We find that there is limited but scattered opportunities for local solar PV manufacturing within African countries. Also, diversifying into the existing global solar PV manufacturing value chain may be challenging due to market concentration, strong entry barriers, and established players. However, we find that the region holds a natural competitive advantage in solar power generation that could provide a sustainable pathway to meet Africa's energy deficit and promote industrial development. Based on these, we discuss the role of a regionalized solar PV industrial policy and strategy for establishing a localized solar PV sector in Africa.

Suggested citation

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Acronyms

AfDB	African Development Bank
BNEF	Bloomberg NEF
CdTe	Cadmium Telluride
c-Si	Crystalline Silicon
CSP	Concentrated Solar Power
DRC	Democratic Republic of Congo
GaAs	Gallium Arsenide
HS	Harmonized System
III-V MJ	multijunction
mc-Si	Multicrystalline Silicon
MG-Si	Metallurgical Grade Silicon
Mono c-Si	monocrystalline silicon
µm	microns
nm	nanometers
poly c-Si	polycrystalline silicon
PV	Photovoltaic
RCA	Revealed Comparative Advantage
sc-Si	Single-Crystalline Silicon
SiO2	Silicon Dioxide
Solar PV	solar photovoltaic
Te	Tellurium
USGS	US Geological Survey

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Introduction

The climate crisis has spurred a global call to accelerate the transition to a low carbon economy. This is entrenched in the global goal not to overshoot the 1.5°C target for global warming agreed upon by 196 countries in the Paris Agreement in 2015 (IPCC, 2022). Accordingly, almost all countries have committed to decarbonizing their economies in the coming decades, with many large corporations announcing ambitious plans and targets to cut their carbon footprints (Altenburg et al., 2022). Besides the quest for a solution to the climate crisis, the frequent conspicuous energy crisis (due to high energy dependence on hydrocarbons), and the consequent need to diversify energy mix and ensure energy security have also contributed to global growth in the demand for clean energy systems and technologies.

Clean energy systems and transition technologies such as solar and wind energy, fuel cells, electric vehicles and green hydrogen, are now globally recognized as plausible pathways to attain a low carbon future. Amid these energy systems and transition technologies, solar photovoltaic cells (solar PV), especially crystalline silicon (c-Si) solar PV, are a key transition technology and an important source of low-emission electricity (IEA, 2023a).1 Solar PV technology is used to generate electric power by using solar cells to convert energy from the sun into a flow of electrons through the photovoltaic effect. Compared to other emerging transition technologies, the solar PV technology is a matured technology, with an already established market and promises to play a key role in attaining a low carbon future (IEA, 2022a; IEA, 2023a). Hence, solar PV technology has experienced unprecedented growth in installations over the years, growing from 40 GW in 2010 to 1,000 GW in 2022. In 2022, solar PV energy generation accounted for 14% of total renewable energy generation (IEA, 2023a: 215).

The solar PV technology-led green transition offers a myriad of opportunities for industrialization and structural transformation, particularly in mineral-rich developing countries. This is because manufacturing solar PV is mineral-intensive and the rapid growth of solar PV manufacturing, for instance, is opening new markets, creating jobs, driving increases in infrastructure investment, as well as, providing opportunities for industrial development (IEA, 2023a). As a result, developing countries are now devising policies and strategies to accelerate solar PV technology-led green transition and to take advantage of the new growth in the demand for critical mineral resources and solar energy economy. This trend could offer African countries a game-changing opportunity for broad-based development due to two main reasons.

Firstly, Africa is endowed with diverse transition minerals critical for rapid green transition (Diene et al., 2022; Andreoni & Avenyo, 2023). Given the mineral-intensive nature of Solar PV, critical mineral rich African countries have a unique opportunity to diversify their local production and integrate into downstream segments of clean energy transition technology value chains. This opportunity is amplified by the geopolitical tensions between Western countries and China, primarily due to Western efforts to diversify supply chains amidst China's dominance in critical minerals exploitation and transition technologies' manufacturing. Africa countries can capitalize on these trends to induce productive investments and build advanced domestic manufacturing capacity in the transition technology value chains.

Secondly, the African continent remains plagued with energy poverty, which has stymied the region's competitiveness and industrialization (Cole et al., 2018; Djeunankan et al., 2024). Recent estimates from IEA (2023b) indicate that about 43% of the total population lack access to electricity, while the figure stands at over 80% for the rural areas. As most African countries have a natural competitive advantage in horizontal solar

1 Section 2 provides a detailed description of the typologies of solar PV.

irradiance levels, they can position themselves as a global superpower for solar energy generation, including addressing their own energy deficit.

These opportunities could also be a mirage given that, historically, mineral-rich African countries have failed to leverage their mineral resources for broad-based development and sustained structural transformation (Andreoni & Avenyo, 2023). Therefore, how African countries leverage their mineral resources, integrate into established global components manufacturing and supply chains, and formulate industrial strategies to capture value becomes crucial. Consequently, several questions remain: what entry points exist for African countries in the solar PV global manufacturing value chain? What industrial policies and strategies are needed for Africa to benefit from the solar energy economy, considering the climate crisis and energy insecurity imperatives?

Against this backdrop, this paper investigates solar PV manufacturing supply chain, maps Africa's mineral resources key for the manufacturing of the solar PV technology, and trade in related activities in the technology's value chain. The paper then explores the prospects for developing a home-grown solar PV manufacturing in Africa, considering: (i) countries' current integration in the solar PV value chain; (ii) natural resource endowments important for manufacturing the technology; (iii) related technological capability; and iv) foreign investment inflows to solar electric power sub-sectors.

Our findings suggest that individually, African countries have extremely limited comparative advantage in terms of critical resource reserves, trade, capabilities, and finance, to integrate into the solar PV manufacturing value chain. At best, the available critical mineral resources and capabilities remain latent and scattered for any meaningful solar PV technology manufacturing-led development. However, given that the continent has a natural advantage in horizontal irradiance levels to generate solar energy, it could seek to install c-Si solar PVs to generate electricity for domestic consumption and to drive an alternative industrial development agenda.

The rest of the paper is organized as follows. The next section describes the solar PV typologies. Section 3 provides an overview of the solar PV and the supply chain in general. Section 4 discusses the opportunities and challenges of manufacturing and adopting solar PV technology in Africa. Section 5 presents a discussion of possible pathways, strategies, and lessons for Africa in a solar-led economy.

Chapter 1. Solar PV technology typologies

Solar PV technologies are comprised of photovoltaic cells primarily designed to receive solar radiation as pure light and convert it into electrical energy. The foremost discovery of the technology is attributed to Edmund Becquerel in France, who more than a century ago, noted that an electric current is produced when two metals immersed in a liquid were exposed to sunlight (Carvalho et al., 2017). The modern solar PV technology, however, is attributed to Russell Ohl, a scientist at Bell Laboratories in New Jersey, USA, who in 1940 discovered that shining light on a mono-crystalline material registered on a voltmeter (Carvalho et al., 2017: 2). Today, the solar PV technology is a key technology in the transition towards greener energy and production systems as well as a low-carbon future.

The literature identifies two main types of photovoltaic cells: the wafer-based and thin-film solar PV cells, respectively (Jean et al., 2015; IEA, 2022a). The wafer-based cells are fabricated on semiconducting wafers and can be handled without an additional substrate, although modules are typically covered with glass for mechanical stability and protection (Jean et al., 2015: 1203). There are about three main types of such technologies including c-Si, Gallium arsenide (GaAs) and III-V multijunction (MJ) solar cells, respectively.2 To date, c-Si remains the predominant wafer-based cells, because of its lower material and manufacturing costs, in comparison to GaAs and III-V MJ solar cells, which have higher solar conversion efficiency (Metaferia et al., 2019).

Thin-film solar cells are typically a few nanometers (nm) to a few microns (µm) thick – much thinner than the wafers used in conventional c-Si solar PV cells, which can be up to 200 µm thick. They are made by additive fabrication processes, consisting of semiconducting films deposited onto a glass, plastic, or metal substrate and then interconnected cells are formed by subsequent back contact processes and scribing (Jean et al., 2015; Scarpulla et al., 2022). This differs from wafer-based (e.g., Si) technologies wherein wafers are individually processed into cells, soldered together, and packaged into modules (Scarpulla et al., 2022:1).

The structure of the thin-film solar cell gives it both production cost and material usage advantage over the wafer-based solar cell. However, many thin-film solar cells have shorter operational lifetimes and larger degradation rates than the wafer-based solar cells, especially c-Si, in accelerated life testing. Akin to this, production equipment for thin-film panels is neither standardized nor available off the shelf. Initial capital expenditure for thin-film production equipment is also relatively high compared to that of c-Si which can be spread along the PV value chain (Bernreuter, 2023). The culmination of these has contributed to the limited deployment of thin-film solar cells.

In general, most thin-film solar cells are classified as second generation, contrasting them mostly from c-Si that is conventionally believed to be the first-generation solar cells (Dambhare et al., 2021; Pastuszak & Węgierek, 2022). This category of solar cells extends from commercial technologies based on conventional inorganic semiconductors, to emerging technologies based on nanostructured materials. Notable examples of commercial thin-film solar cells are as amorphous silicon, cadmium telluride (CdTe), and copper indium gallium diselenide, while examples of the emerging ones include copper zinc tin sulfide, perovskite solar cells, dye-sensitized solar cells, organic photovoltaics, and colloidal quantum dot photovoltaics (Jean et al., 2015).

Although the foregoing discussion indicates distinct types of solar PV technologies, the

2 Crystalline silicon based solar cells are silicon based solar cells and are classified as single-crystalline (sc-Si) or multicrystalline (mc-Si). GaAs are single-junction solar cells consisting of two elements including gallium and arsenide which are widely used in semiconductor technologies, while III-V multijunction (MJ) are solar cells that use a stack of two or more single-junction cells with different bandgaps to absorb light efficiently across the solar spectrum by minimizing thermalization losses.

global solar PV markets and supply chains are dominated by c-Si solar PV and CdTe thin-film PV technology. Table 1 shows the key raw materials that are required to produce c-Si solar PV. According to a recent IEA report, c-Si solar PV accounts for over 95% of global production, while the remaining share is largely accounted for by CdTe thin-film PV technology (IEA, 2022a). Figure 1 shows the evolution of the c-Si solar PV and CdTe thin-film PV technology between 2011-2022, reflecting the dominance c-Si solar PV has in the solar PV markets.

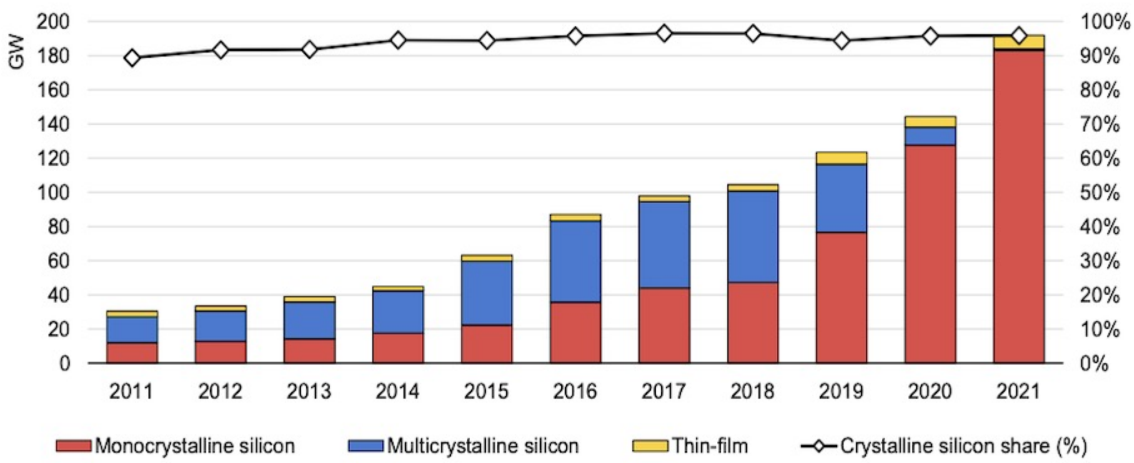
Against this background, the remainder of the paper focuses on the c-Si solar PV, its production and value chain. For completeness, however, we provide a detailed description of the CdTe thin-film PV technology in Appendix A.

Table 1: **Distribution of mineral resources for crystalline silicon solar PV technologies**

Material	Function	C-Si (resource) weight-based	C-Si (resource) Value-based
Silicon	c-Si wafers; in the form of high-purity quartz, for crucibles to grow monocrystalline silicone ingots via the Czochralski process	3-4%	35-45%
Aluminum	Module frame; mounting structure; connectors; back contact; inverters	12-14%	9-12%
Antimony	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerization catalyst)	0.1-0.3%*	N/A
Copper	Cables, wires, ribbons, inverters	2-4%	5-12%
Glass	Module	68-72%	11-15%
Indium	Transparent conducting layer (indium tin oxide) in silicon heterojunction	N/A	N/A
Lead	Soldering paste and ribbon coating in c-Si modules	0.01-0.05%	<0.05
Silver	Electronic contacts: silver paste, busbars, and soldering	0.03-0.08%	9-23%
Tin	Solder, ribbon coating in c-Si modules	0.01-0.05%	0.03-0.1%
Zinc	Galvanized steel in mounting structures	0.03-0.1%	0.03-0.1%

Source: IEA (2022).
**Glass containing antimony*

Figure 1: **Solar PV module production by technology**



Source: IEA (2022a)

Chapter 2. **C-Si solar PV technology: Overview, supply chain, and trends**

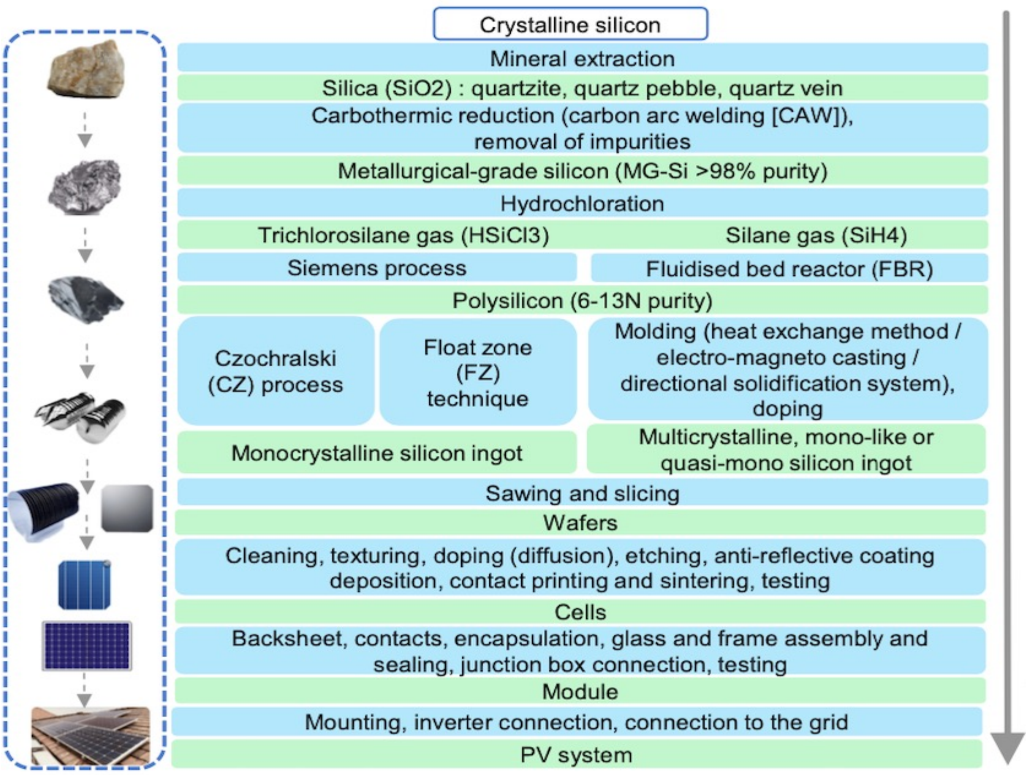
This section provides a detailed overview and description of c-Si solar cell-based modules, their value chain, and trends.

2.1. Overview of c-Si PV technology

As noted, the global production and markets for solar PV are currently dominated by c-Si solar in two forms: monocrystalline (mono c-Si) and polycrystalline (poly c-Si). Mono c-Si solar cells are made of a single silicon crystal, also known as single-crystalline (sc-Si). Poly c-Si solar cells, on the other hand, are made of multiple silicon crystal fragments that are melded together during manufacturing, namely multicrystalline (mc-Si). Although both forms of solar cells achieve the same goal, mono c-Si cells are more efficient than poly c-Si cells. This gain brings with it greater costs and complexity of production when compared to poly c-Si (Qazi, 2017; Ameur et al., 2021).

The basic raw material used in crystalline solar cells is silicon, although other raw materials are required to bring the solar PV to life. Silicon is found in the form of silicon dioxide (SiO2) otherwise known

Figure 2: **c-Si Solar PV manufacturing**



Source: IEA (2022a)

as silica, which is extracted from quartz. In general, silica sand is abundantly available on the planet as it constitutes about 28% of the Earth's crust (Ameur et al., 2021). However, naturally occurring high-grade silica sand - usually silica sand with above 98% purity level - is relatively scarce. The production of c-Si solar-based cells depends on high-grade silica sand, albeit an additional manufacturing process is required to transform it into what is known as solar grade silicon. This transformation entails a two broad manufacturing process that is both costly and energy intensive (see Figure 2).

The first broad process of transforming silica sand into a solar grade silicon involves subjecting the silica sand to a metallurgical purifying process to attain above 99% purity level to arrive at what is known as metallurgical grade silicon (MG-Si). The second broad process involves subjecting the MG-Si to further purification through either a Siemens chlorination process, fluidized bed reactor or an upgraded metallurgical-grade silicon process (Méndez et al., 2021; IEA, 2022a). In either case, this second process is needed to remove such impurities as Fe, Al, B, and P to provide solar grade silicon with 99.99999% purity (Heidari & Anctil, 2022). After this, the resulting solar-grade silicon is crystallized into mono c-Si ingots which are fabricated using Czochralski process or float-zone method. Alternatively, the resulting solar-grade silicon are cast into multicrystalline ingots, which are then sliced into 150–180 µm wafers prior to cell processing (Jean et al., 2015; IEA, 2022a).

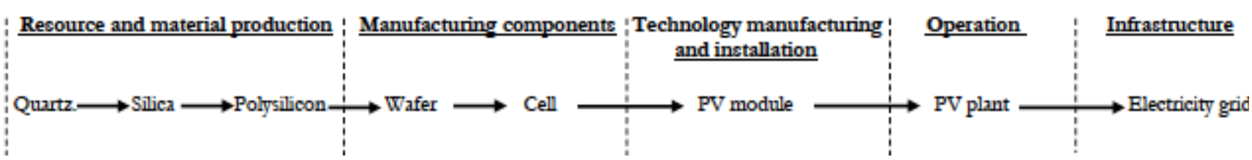
The cell processing stage involves transforming the silicon wafers into solar cells and consists of different steps including texturing, cleaning, doping, etching, and printing silver paste metal connections (IEA, 2022a). After this, the solar cells are then arranged on a backsheet, connected, and laminated with an encapsulating plastic material to form a module. Depending on the module type, it is covered with glass both on the front and backside with an addition of a junction box and an aluminum frame (IEA, 2022a).

2.2. Crystalline silicon solar PV technology value/supply chain

Today, most productions are organized within a value chain that is sliced into value-creating tasks, performed across different cost-saving locations and borders. As such, various parts and components of the c-Si solar PV technology are organized and produced across three value chain segments: upstream (silicon suppliers, polysilicon producers, and ingot and wafer manufacturing), midstream (cell producers, module/panel and system assembling), and downstream (distribution, installation, and electricity generation).[3]

The value chain activities begin with the extraction and conversion of quartz into silicon (see Figure 3). This stage of the value chain activities accounts for about 4% of the overall production costs (Green Rhino Energy, 2023a). As noted previously, silicon is abundantly available, however higher-grade silicon required as input material for polysilicon production are relatively scarce. Technologies needed for quartz mining and silica sand extraction are standardized and can be bought off the shelf. In most cases, except for drying silica sand before transportation to MG-Si facilities, further beneficiation process is not needed for mines with the highest purity (Heidari & Anctil, 2022).

Figure 3: **Solar PV technology value/supply chain**



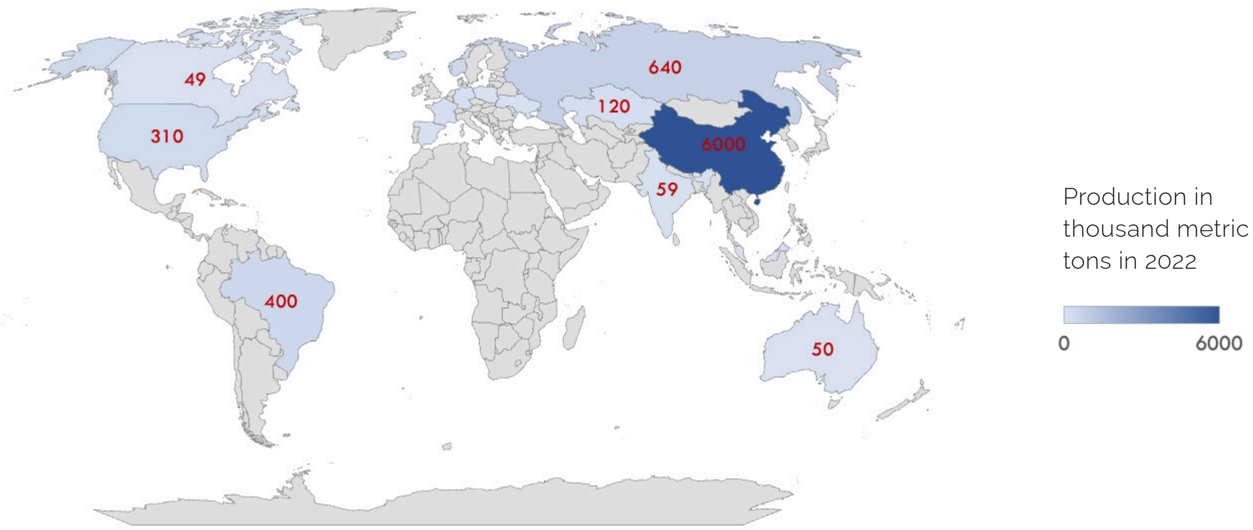
Source: Authors based on IEA (2023a)

3 The thin-film value chain is much shorter, as the modules are manufactured in one single step from raw silicon and other compounds by depositing the photovoltaic material and other chemicals on glass or plastic.

Hence, the ease of integration into this segment of the PV technology value chain can be determined by a country's natural resource endowment.

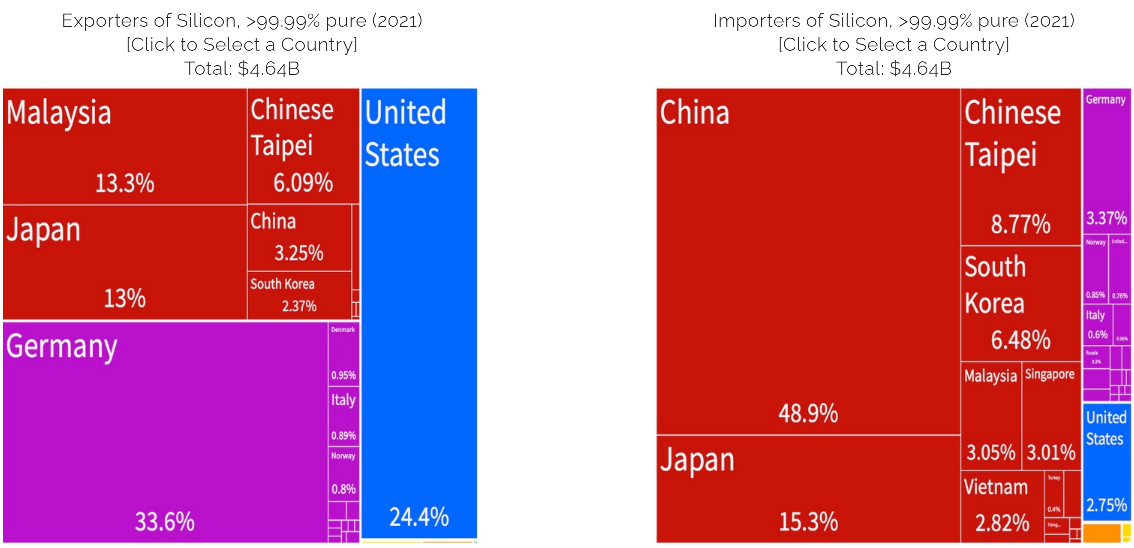
Figure 4 shows the global distribution and production of silicon, respectively. The figures shows that no African country produces silicon. In 2022, China was the world's largest silicon producer, producing about six million metric tons out of the estimated 8.8 million metric tons total global production. The second largest global producer of this metalloid was Russia, producing 640,000 metric tons in the same year (Garside, 2023). Notably, China is the highest silicon producer, but most of China's quartz products are below medium grade and applicable only to low-end industries (Zhou & Yang, 2018). As such, China relies on lower-grade silica resources or import high-quality sands from other countries to produce silicon. That being said, the country can purify its lower-grade silica by exploiting its high coal deposits to power industrial activities. Additionally, evidence also shows that China is the highest importer of pure silicon (see Figure 5), sourced primarily from the USA and Vietnam until 2012, and now Cambodia, Australia, Malaysia, and Pakistan (Heidari & Anctil, 2022).

Figure 4: **Major silicon producers in 2022 (in 1,000 metric tons)**



Source: Authors based on data from USGS (2023)

Figure 5: **Major exporter and importers of high-grade silicon**



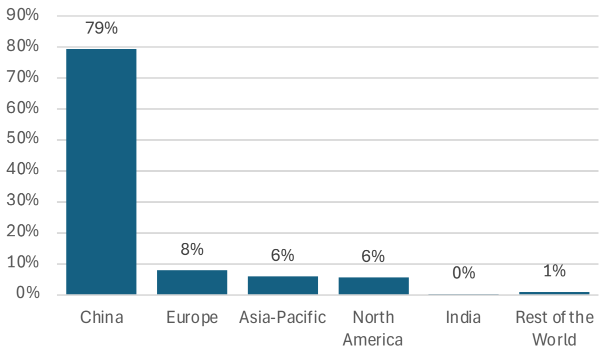
Source: OEC (2023)

Closely tied to the activity defined above is polysilicon production, which accounts for about 30% of the module's total value and 21% of the system's total value (Green Rhino Energy, 2023b). Polysilicon production is associated with huge upfront costs in setting up the manufacturing facility, as well as huge running costs to meet up the energy intensiveness of the fabrication process. Furthermore, the production of polysilicon requires advanced technologies and very specific know-how to control all the parameters of the chemical reactions to be able to produce silicon at a competitive price (Carvalho et al., 2017). Hence, integration into this segment of the value chain is dependent on significant financial, energy and technical capacities, creating high barriers of entry. As shown in Figure 6, this segment is dominated by China, with the region accounting for about 79.4% of the globally produced polysilicon used for solar PV in 2021. Consequently, majority of companies producing solar PV are in China (Table 2). Interestingly, before China attained this near-monopoly position, it shared competitive market positions with countries like United States, Malaysia, Korea, Japan, and Germany (IEA, 2022a; also see Carvalho et al., 2017).

Next to the polysilicon is the fabrication of ingot, which is followed by cutting the ingot into wafers. Both activities jointly account for about 27% of the module's total value and 15% of the system's total value (Green Rhino Energy, 2023b) and are the second most energy intensive after polysilicon (IEA, 2022). The activities undertaken in both stages are cost-intensive but standardized in terms of production processes and technologies used. Hence, there is a lower barrier of entry into this segment provided the initial cost outlay can be met. At best, the notable barrier is that polysilicon producers forward-integrate in a bid to capture more stable value, resulting into a direct competition with established wafer cutters. Based on 2019 estimates from Bernreuter Research, China currently accounts for 95% of the manufacturing capacity for Ingot and 97% manufacturing capacity for wafer (Bernreuter, 2023). Recent estimates from IEA (2022a) shows that China still accounts for 97% of global manufacturing capacity for wafers (see Figure 7: a and b).

The fifth stage of the value chain activity is cell manufacturing, involving the production of the p-n junction responsible for the photovoltaic effect. Integration into this chain activity is limited due to the significant capital requirements for the manufacturing line, combined with the need for economies of scale that enable dominant firms to engage favorably in price competition and quality differentiation. Estimates from Green Rhino Energy (2023b) indicate that this stage of the value segment accounts for about 27% of the module's total value and 19% of the system's total value, making it the value chain segment with the highest value capture after polysilicon producers. Much of this value accrues to China, which has consistently accounted for a greater manufacturing capacity share since 2010 (see Figure 7).

Figure 6: **Distribution of share of global solar polysilicon manufacturing capacity in 2021**



Source: Statista (2023a)

Table 2: **Global production capacity of the leading polysilicon manufacturers in 2020**

Companies	Production capacity in metric tons
Tongwei	96,000
GCL-Poly	90,000
Wacker	84,000
Daqo New Energy	80,000
Xinte Energy	80,000
East Hope	40,000

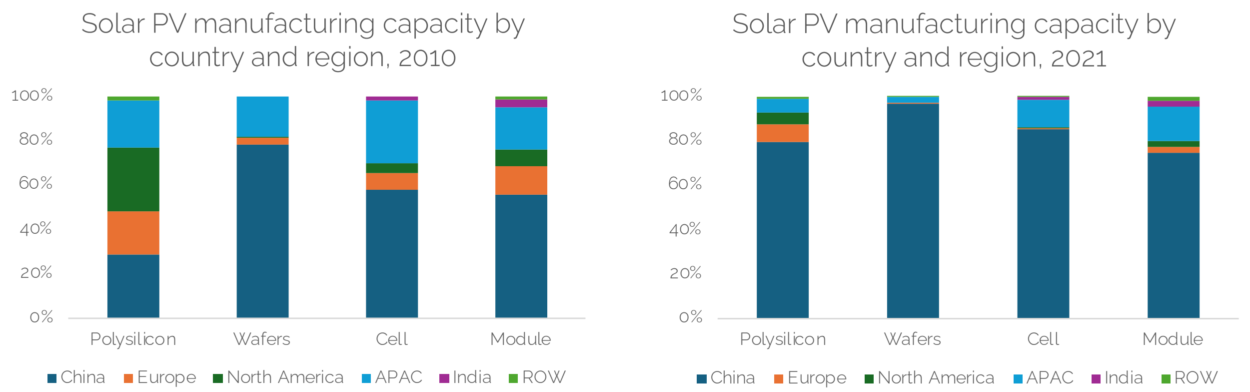
Source: Statista (2023b)

Solar PV panel/module assembly follows the cell manufacturing stage. It involves soldering solar cells together and applying electrical junctions and glass sheets to the soldered cells to form a module. There is a lower barrier for new firms' entry into this chain activity due to relatively lower capital requirements and technological complexity for the manufacturing line. Accordingly, this segment of the value chain is more globally dispersed, with recent estimates from the IEA indicating that about 38 countries have module assembly facilities (IEA, 2022a). However, China is still responsible for about 74.7% of global production in 2021, up from 55.7% in 2010 (see Figure 7). The supply chain stages that follow this are the operation and electricity grids, also dominated by China.

2.3. Solar PV Technology Trends

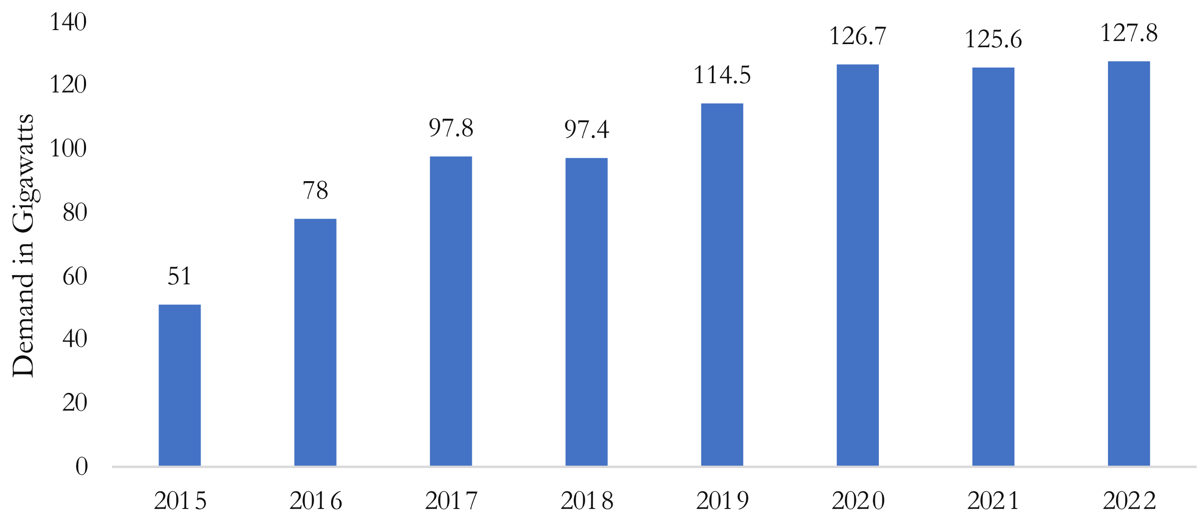
The global market for solar PV technologies has grown exponentially over the years and has undergone several innovations. Figures 8-12 show some of the basic trends in the solar market. Figure 8 illustrates the evolution of global demand for solar PV power between 2015 and 2022. Consistent with our earlier conjecture in the introduction, the figure highlights that global demand for solar PV has, on average, been on the rise over the past eight years. A recent forecast from the IEA also indicates the annual solar PV capacity additions will increase every year for the next five years.

Figure 7: **Solar PV manufacturing capacity by country and region**



Source: IEA 2022

Figure 8: **Global demand of solar PV power**



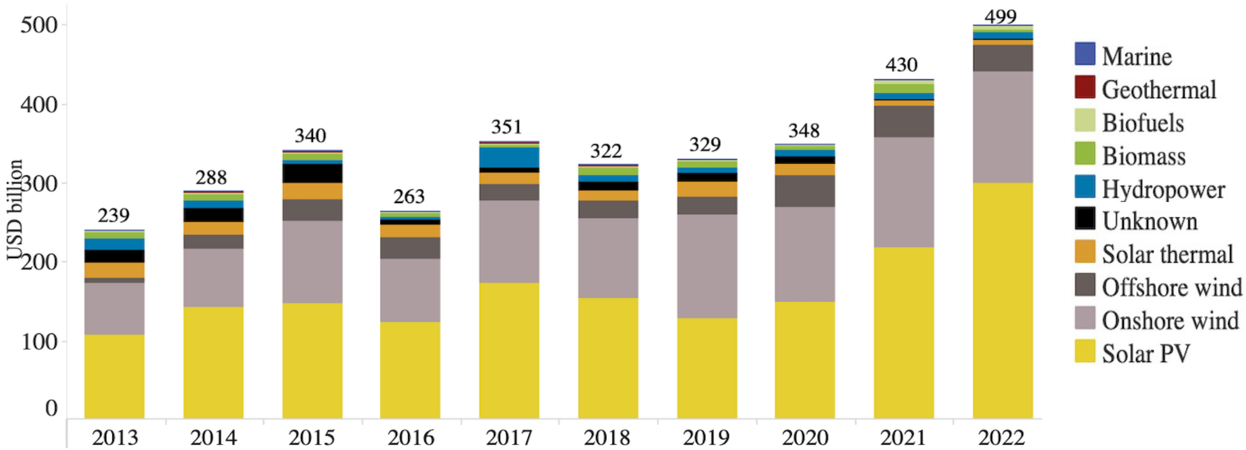
Source: Statista (2023c)

Furthermore, solar PV's installed power capacity is poised to surpass that of coal by 2027, becoming the largest in the world (IEA, 2022b). With c-Si being a dominant solar PV technology, it is not surprising that the recent forecast from the Technavio market research report predicts that the c-Si solar PV market size will grow by USD 56 billion (EUR 51 billion) from 2022 to 2027, progressing at a CAGR of 18.17%. Unfortunately for Africa, about 60% of this market's overall growth is expected to originate from APAC, with China, India, Japan, Australia, and South Korea being the major contributors (Technavio, 2023).

Figure 9 provides an overview of global transition technology energy investment trends. The figure indicates that solar PV has been a major beneficiary of financing and investment in transition energy technologies, more disproportionately than other technologies. Specifically, it accounts for about 46% of global renewable and transition technology energy investment between 2013 and 2022. Second to this, is offshore wind, which attracted 32% of global renewable energy investment during the same period, while the remaining 22% went to other technologies (IRENA & CPI, 2023).

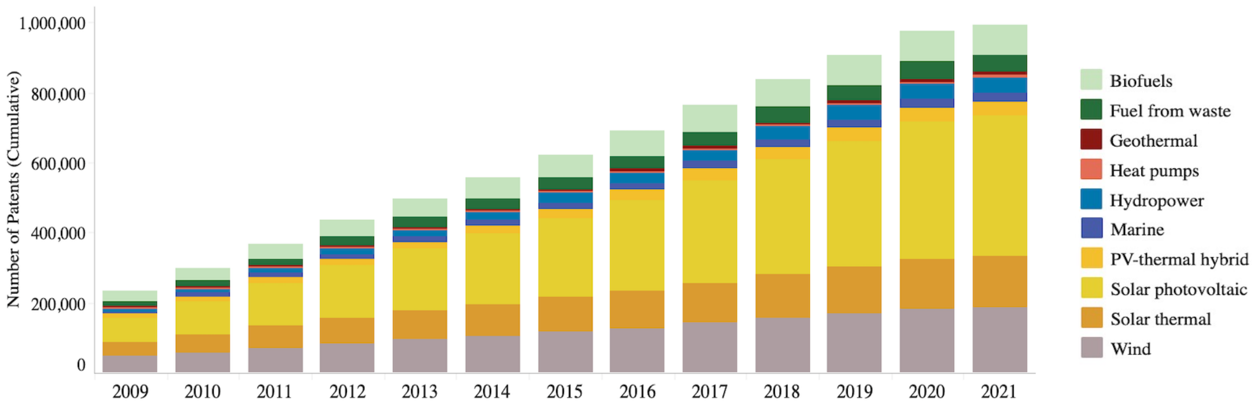
Figure 10 shows the evolution of innovation in clean and transition energy technologies. Unsurprisingly, solar PV technology emerges with the highest innovation as measured by the number of patents. While the available data do not allow us to track the type of solar PV,

Figure 9: **Annual financial commitments in renewable energy**



Source: IRENA & CPI (2023)

Figure 10: **Renewable energy patents evolution**



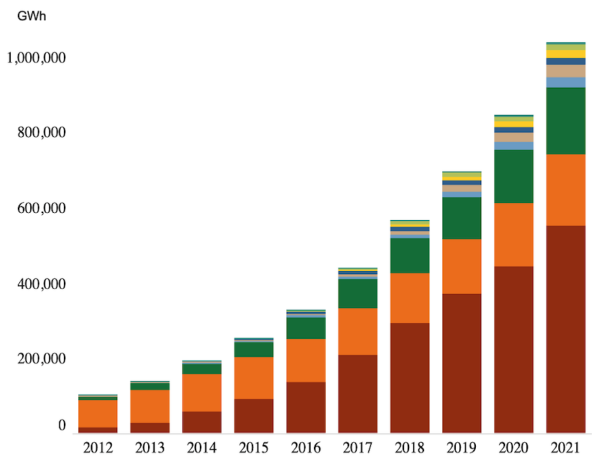
Source: IRENA (2022a)

it is reasonable to suggest that a large share of these innovations is attributable to the c-Si technology since it is the dominant technology in the solar PV market. This argument is consistent with the predominant narrative that economies of scale and continuous innovation throughout the solar PV sector have contributed to the cost competitiveness of solar PV manufacturing, making the relative price of the technology cheaper (Carvalho et al., 2017; IEA, 2022a). This, in turn, has contributed to its diffusion and wide adoption while increasing entry barriers into the industry.

The foregoing discussion reinforces the earlier conjecture that solar PV is a matured technology with a well-established market and promises to play a key role in attaining a low-carbon future. In this case, African countries stand to gain not just by diversifying into the value chain but also by deploying the technology. To gain a better perspective on the diffusion of the solar PV, Figure 11 (a and b) shows the regional trends on solar electricity capacity (Figure 11a) and solar electricity generation (Figure 11b). Consecutively, the top three regions for solar electricity capacity and generation are Asia, Europe, and Central America and the Caribbean. On the other hand, African countries, on average, have an infinitesimally low solar electricity capacity and generation.

Figure 12 shows the top 10 countries with the highest solar PV power capacity or electricity

Figure 11a: **Solar energy installed capacity, regional trend**



Source: *IRENA (2022a)*

Figure 11b: **Solar electricity generation, regional trend**

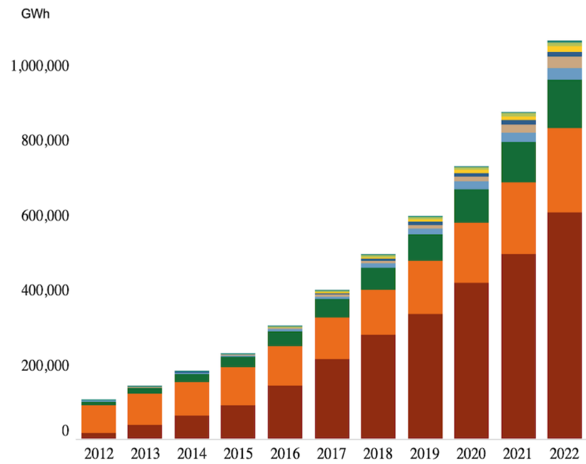
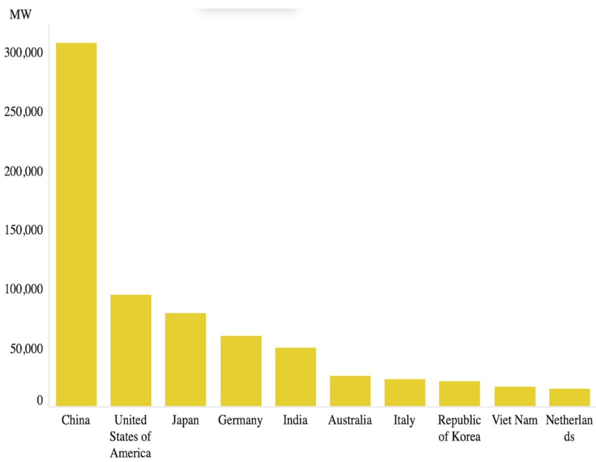
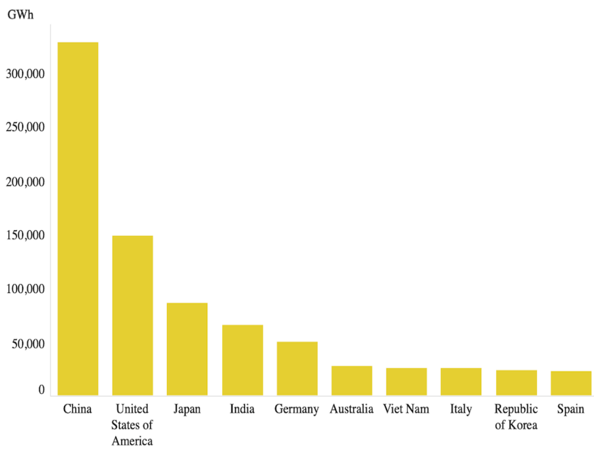


Figure 12a: **Solar PV install capacity, 2021**



Source: *IRENA (2023)*

Figure 12b: **Solar PV electricity generation capacity, 2021**



generation. Again, none of the countries in Africa made it to the list. This is not surprising, as only 2% of the global investments in renewable energy over the last two decades (i.e., between 2000 and 2020) went to Africa, with significant regional disparities (IRENA, 2022b). This anecdotal evidence underscores the limited role of solar energy in Africa's current energy mix, despite countries in the region holding a competitive advantage in horizontal irradiance levels that could turn them into superpowers for solar energy generation and enable them to build other linked local manufacturing capabilities in related and unrelated manufacturing sub-sectors. Hence, African countries are not just excluded from the global solar PV production system but have also been abysmally poor in the deployment of the technology, partly due to the relative cost of these related technologies.

Chapter 3. Towards c-Si solar PV manufacturing in Africa: Opportunities and challenges

The preceding section reveals that the global solar PV market and supply chains are concentrated in and dominated by China. The evidence highlights that China controls about 80% of all manufacturing stages globally, while holding a dominant position along each segment of the value chain. More importantly, it also reveals that production of solar PV is extremely limited in Africa as none of the countries in the region hold any significant role in the manufacturing stages globally. At best, Germany, USA, and some other Asian countries ,such as Vietnam, Malaysia, Japan, India, and Korea, hold some market share in certain segments of the solar PV value chain such as cell and module manufacturing capacity. Hence, African countries not only have a very low solar installed capacity, as shown in section 2.1, but are also excluded from the global production system of c-Si solar PV.

As noted earlier, Africa is endowed with key transition minerals as well as significant potential for solar energy generation, given the natural competitive advantage many African countries have in the horizontal irradiance levels. In line with the foregoing discussion, this section examines the prospect of African countries diversifying, integrating, and upgrading into the solar PV value chain from a resource-led perspective. We do this by mapping Africa's: i) mineral reserves and production; ii) related technological capability; and iii) foreign capital investments relevant for c-Si solar PV technology manufacturing.

3.1. C-Si solar PV minerals in Africa: Stock and production distribution

As noted, the production of solar PV is mineral-intensive, with recent estimates indicating that raw materials alone make up 35%-50% of the total cost of a solar PV module (IEA, 2022). Table 1 lists and describes the requisite resource materials needed to produce solar PV technology. To understand the possible opportunities for local and regional solar PV technology manufacturing from a resource-led perspective in Africa, we map the spatial distribution of the identified raw materials needed for solar PV technology in Africa. Based on 2023 data from the widely used US Geological Survey (USGS), we track Africa's share of these mineral deposits/reserves and production.4

Figures 13 (a and b) and 14 (a and b) show the deposits/reserves and production of requisite resource materials across African countries. The data show that only two of the mineral resources - copper and tin - required to produce solar PV are available and produced on the African continent. While these are mainly found in the DRC and Zambia, the production of tin also occurs in Nigeria and Rwanda. Despite this, the continent's share in terms of reserves and production is still negligible globally, particularly for a solar PV-led manufacturing strategy envisaged on the continent. This raises questions about the specific approaches Africa can leverage to integrate and capture value in these emerging technologies.

Given the emerging evidence that African countries lack the minerals critical for competitive c-Si solar PV manufacturing, we explore the

4 Appendix B identifies African countries as well as the countries with the highest reserves and production of solar PV minerals globally.

potential for solar PV energy generation. Africa is a global superpower for solar energy generation given the natural competitive advantage most African countries have in horizontal irradiance levels. Figure 15 shows the global horizontal irradiance. The figure indicates that most African countries have a competitive advantage in terms of their highest horizontal irradiance levels, hence having the potential to generate the highest level of electricity using solar panels installed on the continent. This suggests that there is potential to deploy solar PV technology to generate clean energy to meet the continent's energy deficit and to spur industrial development.

3.2. c-Si solar PV minerals trade by Africa

To complement our analysis, we refer to the BACI-CEPII trade data to make inferences based on African countries exporting these raw materials. However, we note that inferences based on export data should be interpreted with caution, as the export data is prone to re-export. Bearing this in mind, the result for the exercise is reported in Figure 16 and is based on the average export of these materials between 2017 to 2021. The grey shaded boxes signify the country exports processed

Figure 13a: **Share of global reserves of copper in Africa in 2022 (%)**

Figure 13b: **Share of global reserves of tin in Africa in 2022 (%)**

Source: IRENA (2022a)

Figure 14a: **Share of global production of copper in Africa in 2022 (%)**

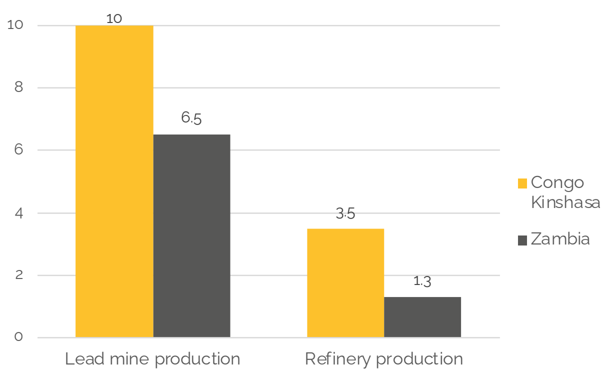
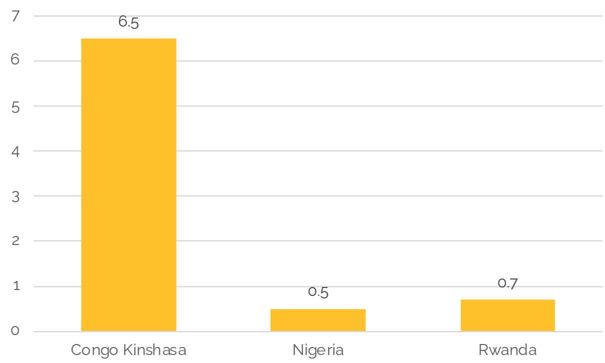
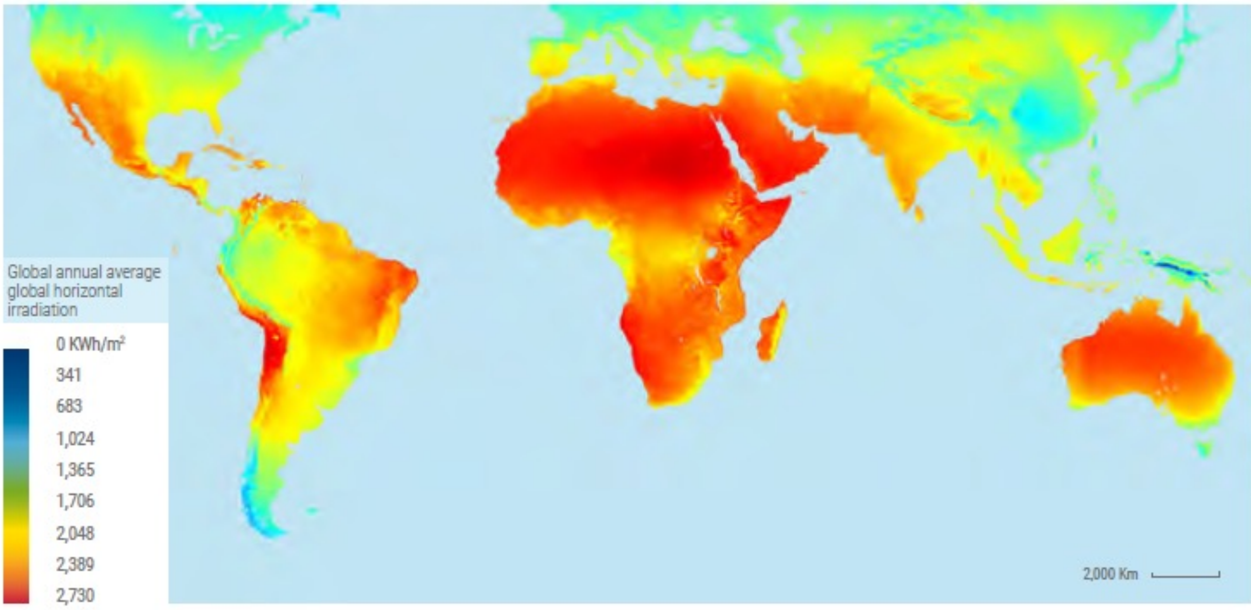


Figure 14b: **Share of global production of tin in Africa in 2022 (%)**



Source: Authors based on data from USGS (2023)

Figure 15: **Global solar resources map (Global horizontal irradiance)**



Source: https://globalsolaratlas.info/download/world

intermediates of the raw material. Blue signifies the country exports primary intermediates of the raw material. Green signifies the country exports both primary and processed intermediates of the raw material, while white signifies no export. Appendix C describes the Harmonized System (HS) classification codes associated with each identified product.

Figure 16 shows that each country in Africa exports at least one of the identified resource materials, either in the primary or processed intermediate form. Aluminum, copper and glass is exported by all 54 African countries in our sample. This is followed by lead and zinc, which are exported by 50 and 49 African countries, respectively. The least exported raw material is antimony, which is exported by only 17 African countries. This is followed by indium, exported by 19 countries. Further, the average number of resource materials exported by each country in the region is eight. Seven countries including Morocco, Nigeria, Namibia, Kenya, Cameroon, Botswana and South Africa, export the highest number of the identified resource materials, with each exporting all the 11 raw materials that are important for c-Si based solar based cells. About 10 African countries also individually export 10 out of the 11 resource materials, while the remaining countries export a minimum of four resource materials. Overall, Figure 18 highlights the prevalence of export activity for the resource materials needed to produce solar PV technology in Africa. The evidence from the trade data contrasts sharply with the mineral reserves and production data highlighted above. This contradiction may be due to a lack or limited data on mineral reserves and production, highlighting the need to improve geological services on the continent.

In what follows, we explore Africa's export destinations for these resource materials. The result of this exercise are reported in Figure 17. Asia tops the list as the region with the highest shares of Africa's resource material exports. Asia accounts for Africa's highest export shares for eight raw materials, including silicon (54%), antimony (37%), copper (61%), tin (90%), indium (78%), lead (60%), silver (49%), and zinc (52%). This is followed by intra-Africa trade, which accounts for the highest export shares of glass (40%), then Europe accounting for the highest export shares of two raw materials: aluminum (43%) and molybdenum (74%). Hence, although Figure 19 indicates a prevalence of exports of the raw materials needed to produce c-Si solar PV from Africa, the continent has primarily served as a supplier of these raw materials to producers outside of the region. This poses the question of whether there are opportunities for beneficiation on the continent.

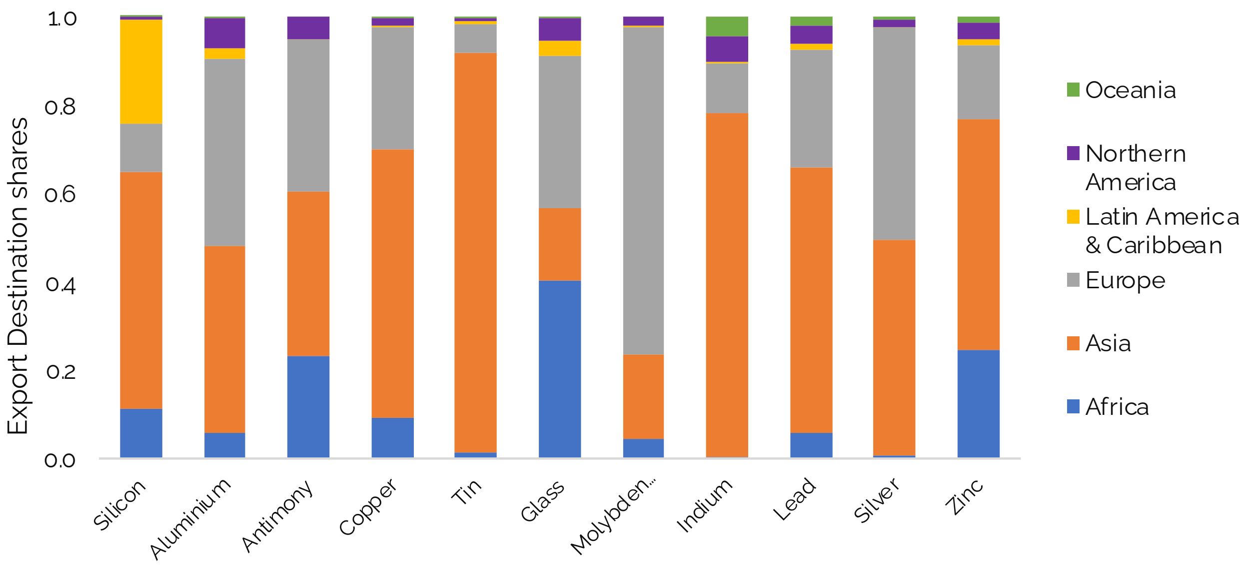
Figure 16: **Export of solar PV mineral by African countries 2017-2021**

Country	ISO3	Si	Al	An	Co	Ti	Gl	Mo	In	Le	Sl	Zi
Algeria	DZA											
Angola	AGO											
Benin	BEN											
Botswana	BWA											
Burkina Faso	BFA											
Burundi	BDI											
Cabo Verde	CPV											
Cameroon	CMR											
Central African Rep.	CAF											
Chad	TCD											
Comoros	COM											
Congo	COG											
Côte d'Ivoire	CIV											
Dem. Rep. of Congo	COD											
Djibouti	DJI											
Egypt	EGY											
Equatorial Guinea	GNQ											
Eritrea	ERI											
Ethiopia	ETH											
Gabon	GAB											
Gambia	GMB											
Ghana	GHA											
Guinea	GIN											
Guinea-Bissau	GNB											
Kenya	KEN											
Lesotho	LSO											
Liberia	LBR											
Libya	LBY											
Madagascar	MDG											
Malawi	MWI											
Mali	MLI											
Mauritania	MRT											
Mauritius	MUS											
Morocco	MAR											
Mozambique	MOZ											
Namibia	NAM											
Niger	NER											
Nigeria	NGA											
Rwanda	RWA											
Sao Tome & Principe	STP											
Senegal	SEN											
Seychelles	SYC											
Sierra Leone	SLE											
Somalia	SOM											
South Africa	ZAF											
South Sudan	SSD											
Sudan	SDN											
Swaziland	SWZ											
Togo	TGO											
Tunisia	TUN											
Uganda	UGA											
Tanzania	TZA											
Zambia	ZMB											
Zimbabwe	ZWE											
Africa (Total)	AFR	0	51	12	53	24	36	11	0	45	0	37
Africa (Total)	AFR	28	54	10	54	38	54	15	19	43	43	46
Africa (Total)	AFR	28	54	17	54	40	54	20	19	50	43	49

Note: Si=Silica; Al=Aluminum; An=Antimony; Co=Copper; Ti=Tin; Gl=Glass; Mo=Molybdenum; In=Indium; Le=Lead; Sl=Silver; Zi=Zinc; Grey signifies the country exports processed intermediate of the raw material. Blue Signifies the country exports primary intermediate of the raw material; Green signifies the country exports both primary and processed intermediate of the raw material, while white signifies no export.

Source: Authors based on BACI-CEPII trade data

Figure 17: **Africa's export destinations for solar PV minerals 2017-2021**



Source: Authors based on BACI-CEPII trade data

3.3. Related technological capability for c-Si solar PV manufacturing in Africa

Do African countries have latent productive capabilities in related products that could be diversified into solar PV manufacturing? One of the sub-sectors most related to the solar PV is the semiconductor and the electronics industry. Available evidence indicates that Chinese firms were able to integrate and upgrade in the solar PV value chain by purchasing production equipment from Western providers while applying their pre-existing technological capabilities in the semiconductor industry to manufacture the various components of the solar modules (see de la Tour et al. 2011; Wu & Mathews, 2012; Carvalho et al., 2017). Accordingly, we evaluate the technological capability of African countries in the semiconductor and electronics industry. This enables us to gauge the prospects of African countries to diversify into solar PV technology manufacturing in the future. To do this, we explore each country's relative competitiveness in the semiconductor and electronics industry using the revealed comparative advantage (RCA) approach.

Consistent with the previous section, our analysis relies on a country's average export between 2017-2021, drawn from the BACI-CEPII.[5] Since the BACI-CEPII data is only available at the six-digit HS code, we built a crosswalk to the 4-digit ISIC Revision 4, which enables us to observe and compute the RCA at the sector level. The 4-digit ISIC Revision 4 yields several sectors that could be associated with the semiconductor and electronics industry. We identified ten 4-digit sectors that, based on the sector definition as presented in the ISIC classification, are more closely related to the semiconductor and electronics sector. Our assessment of a country's technological capability in the semiconductor and electronics industry is based on the average RCA across these ten sectors for each country.

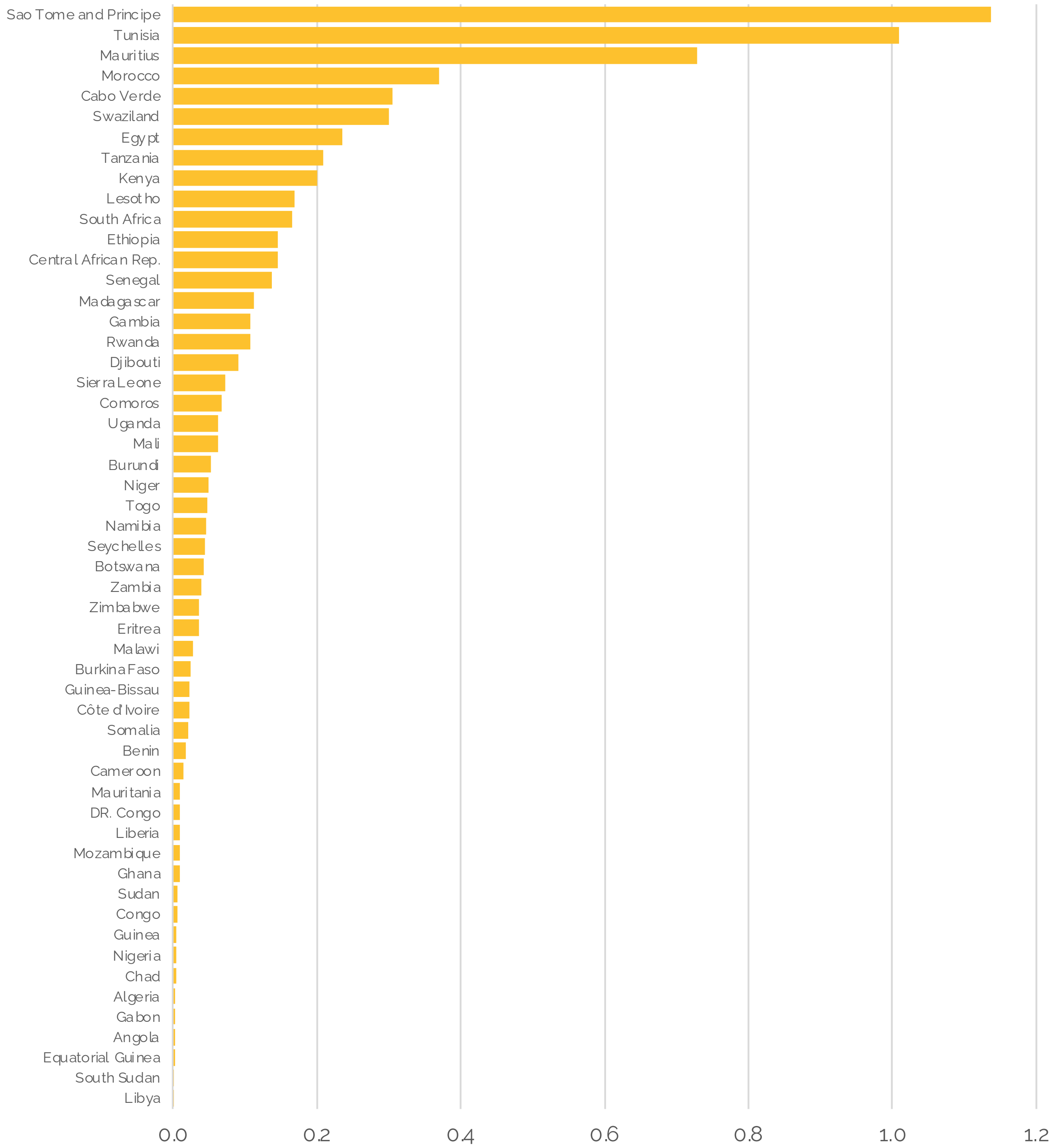
The RCA is computed as a country's share of the 4-digit sector exports in total exports relative to the world's share of 4-digit sector exports in the world's total exports. A resulting high RCA (≥1) corresponds to highly developed and existing production capabilities, which manifests in the sector's global competitiveness. Sectors with

5 See appendix D for further detail on this.

an RCA less than unity are considered to have a comparative disadvantage and are therefore not globally competitive. Within this category, however, there may be sectors with an emerging comparative advantage - i.e., sectors that are developing production and export capabilities and are at the brink of becoming globally competitive manufacturing sectors. We refer to these sectors as those with 0.3 ≤ RCA < 1.

Figure 18 shows the results of this exercise. Only two African countries, Tunisia and Sao Tomé and Príncipe, have an RCA ≥1. Tunisia has an RCA

Figure 18: **Revealed comparative advantage (RCA) in the semi-conductor and the electronics industry in Africa 2017-2011**



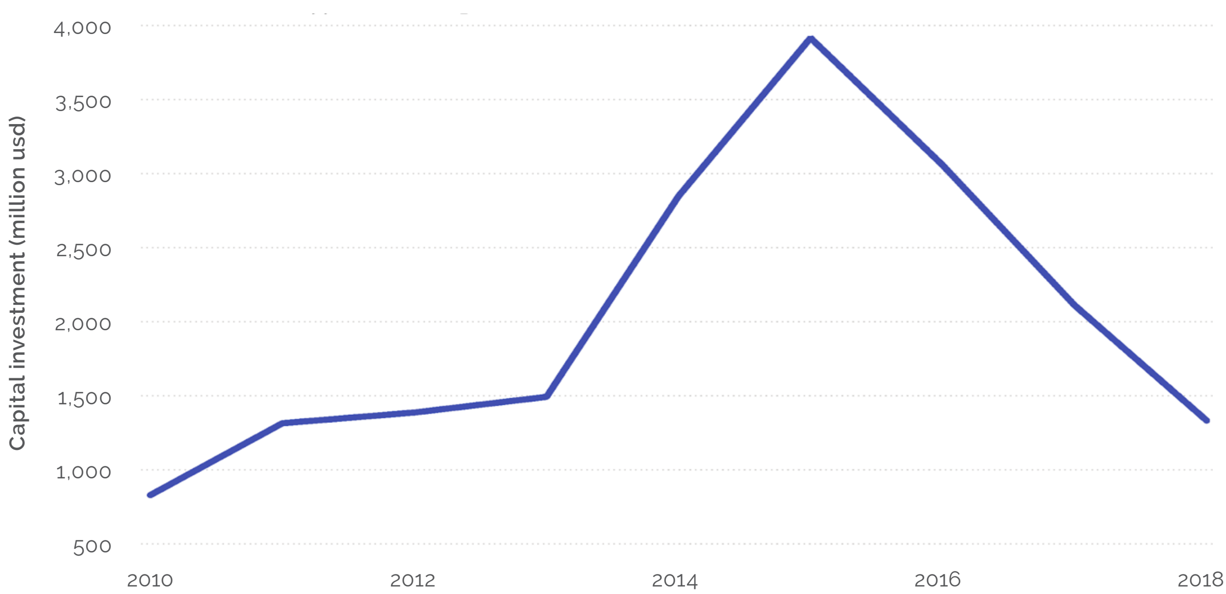
Source: Authors based on BACI-CEPII database score of approximately 1, while Sao Tomé and Príncipe has an RCA score of 1.1, making the latter the country with the highest RCA in the region. In addition to this, we identified five countries with emerging technological capability. This includes Swaziland with an RCA score of 0.3, Cabo Verde with an RCA score of 0.31, Morocco with an RCA score of 0.37, and Mauritius with an RCA score of 0.73. Altogether, the emerging evidence highlights that there are only pockets of technological capability in the region to diversify into solar PV manufacturing in the future.

3.4. Pulling dynamics: investments in solar PV

Clean energy technologies manufacturing is also capital intensive. Given the financial constraints and poor fiscal space that besiege several African countries, domestic manufacturing of clean technologies, such as the solar PV technology, would require significant foreign investments as a push factor. To further understand how African countries are taking advantage of the solar-led economy and inducing investments in renewables, we examine the inflow of foreign direct investments into the solar electric power sub-sector using data from the FDI Markets database between 2010 and 2018. Figures 19 and 20 show a declining level in capital investments in the solar electric power sub-sector in Africa since 2015, almost reaching 2011 level of USD 1.3 billion (EUR 1.2 billion). We observe similar trends across regions, with capital investments to North Africa and SSA regions dropping since 2015 and 2016, respectively.

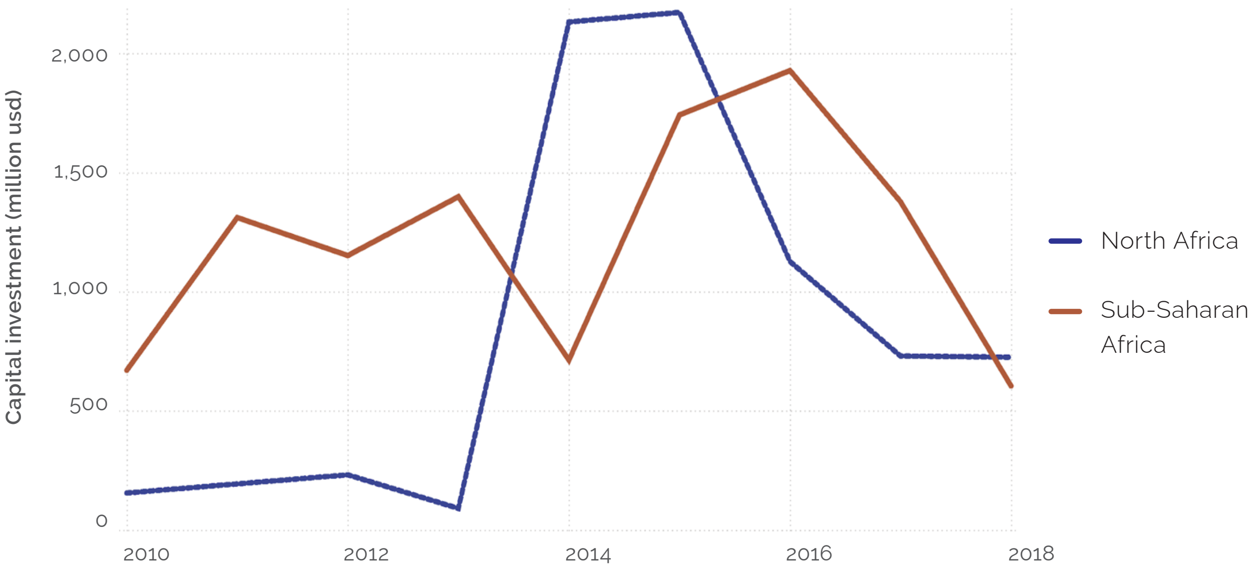
Despite this, some countries remain key destinations for capital investments in the solar electric power sub-sector in Africa. This may be due to their endowments in other natural mineral resources, available productive capability, or a combination of several factors. Our data shows that South Africa, Egypt, and Morocco remain key destinations and received the highest capital investments on the continent between 2010 and 2018 (Figure 21). This indicates that despite the lack of solar PV manufacturing in Africa, solar PV installations are inducing significant amount of foreign direct investments into countries with some latent productive capabilities and scattered mineral resources on the continent.

Figure 19: **Capital investments (million USD) in solar electric power sub-sector in Africa between 2010-2018**



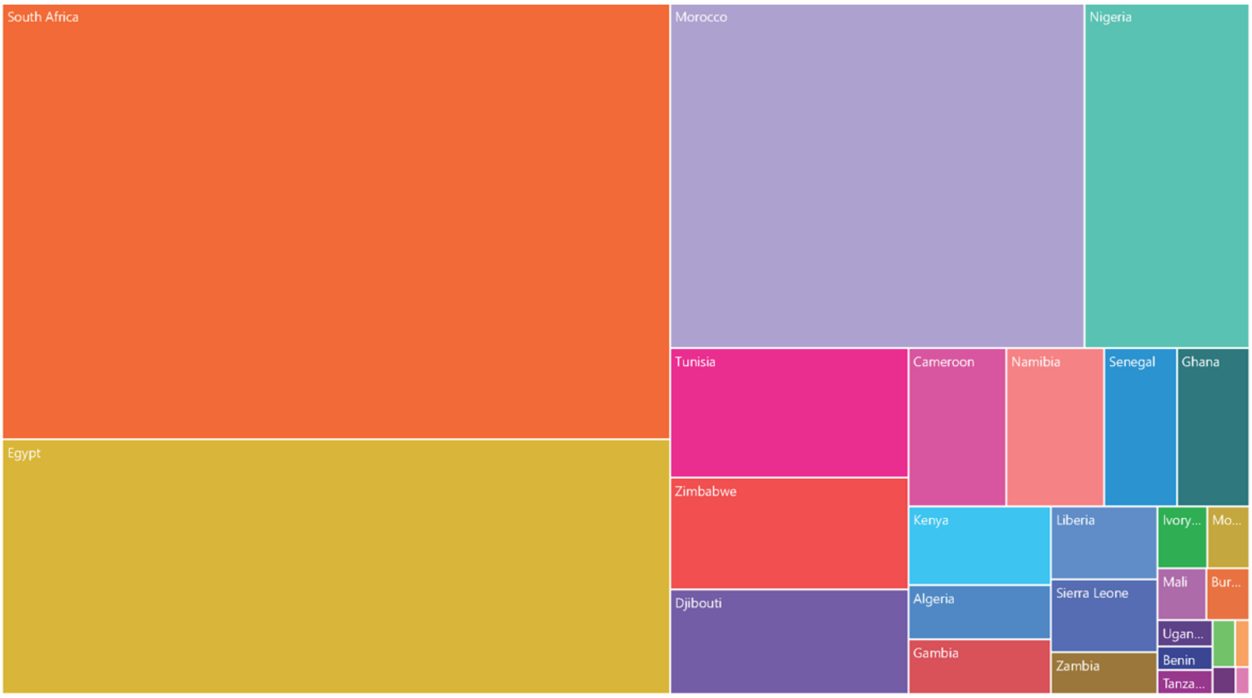
Source: Authors based on data from FDI markets

Figure 20: **Capital investments (million USD) in solar electric power sub-sector across African regions between 2010-2018**



Source: Authors based on data from FDI markets

Figure 21: **Capital investments (million USD) in solar electric power sub-sector by country between 2010-2018**



Source: Authors based on data from FDI markets

Chapter 4. **Towards a new imperative for a regionalized solar PV strategy in Africa**

The new industrial age, fueled by the manufacturing of several mineral-intensive transition technologies, offers potential opportunities for industrialization and structural transformation, particularly in mineral-rich developing regions such as Africa. This paper used data on critical minerals, trade, and investment flows in solar electric power sub-sector to explore how African countries can leverage their natural resource endowments, trade, and productive capabilities for the manufacturing of solar PV.

Our findings reveal a bleak picture for solar PV manufacturing-led industrialization in Africa, with countries having little or no opportunity to upgrade within the existing solar PV value chain. This is because the global solar value chain is well-developed and concentrated, with China controlling more than 80% of each segment. The rest are shared among a few firms in the global North. Even worse, African countries have limited related technological capability and investments crucial for developing solar PV. They also do not hold a comparative advantage in the key resources needed to produce the technology. While the latter conclusion draws from critical minerals data, export trade data reveals that each country in Africa exports at least one of the key raw materials in its primary or processed form. On the downside, a greater share of these exports goes to countries outside the region.

However, we observe some opportunities for solar PV electricity generation-led development on the continent, particularly in related activities in the module assembly and power generation stages of the supply chain, in line with other available evidence in the literature. This offers countries in the region an alternative pathway to address their energy deficit and an opportunity to build other linked local manufacturing capabilities in related and unrelated manufacturing sub-sectors. But does this mean African countries are or should be precluded from developing a viable solar PV manufacturing sector and integrating into downstream segments of the supply chain? There is no direct answer to this question based on the evidence revealed above. However, several lessons can be learnt from China in this regard.

Anecdotal evidence suggests an interplay of factors behind China's eventual emergence as a global player and quasi-monopolist in the entire solar PV value chain. Amongst these possible factors, three are worth highlighting: preexisting related technological capability, availability of complementary resources, and intentional industrial policy. Regarding related technological capability, Chinese firms had a preexisting technological capability in the semiconductor and electronics industry, a sector most closely related to the solar PV industry. Accordingly, at the outset of solar PV industrialization, while Chinese firms mostly acquired PV technologies by purchasing production equipment from international suppliers (Carvalho et al., 2017), they leveraged their related technological capability to build a stronger domestic solar PV sector that dwarfed that of its contemporaries.

Concerning the availability of complementary resources, several activities in the solar PV value chain are energy intensive, including producing polysilicon. China's coal deposits and their exploitation to power industrial activities enabled the country to overcome this hurdle along the value chain segments, thus providing the much-needed complementary asset to establish its own end-to-end solar supply chain. Finally, regarding the Chinese government rolled out different strategies to encourage home-grown solar PV technologies, as per its industrial policy. This included offering cheap land and tax credits to solar-producing firms and startups, prioritizing polysilicon in public research funding, and providing loans from state banks (on friendly financing terms) worth tens of millions of US dollars to solar-producing firms, including startups with no proven track record. Additionally, the Chinese government created demand for the products with generous subsidies, while Chinese factories worked to improve efficiency and reduce costs (Dlouhy, 2021).

This highlights the importance of a solar PV strategy that any African country intending to develop a solar PV sector can emulate. Yet, this may be a tough route for any single African country given the international political economy implications, the low economic and bargaining power of African countries, and the several other challenges such as fiscal constraints and lack of political will that limit a country's ability to solely propel the requisite solar PV strategy. For instance, diversifying into solar PV manufacturing competitively also means reaching scale-investment thresholds. For example, greenfield polysilicon plants are not usually bankable for capacities of less than 10 000 Mt (around 3 GW). In China, plant sizes ranges from 40 000 Mt to 100 000 Mt (IEA, 2022a). This entails a huge capital investment that Chinese entrepreneurs were able to achieve due to huge government direct and indirect support. Unfortunately, most African countries lack the fiscal space to follow suit as financial constraints remain a significant issue in the region (see Konte & Ndubuisi, 2021), exacerbated by long-term credit contract challenges (Maimbo et al., 2011). For many African countries, this is not simply a financial challenge, but also an organizational capability one (Andreoni & Avenyo, 2023). Additionally, energy poverty and poor infrastructure that plague the region (Maimbo et al., 2011) are major issues that need careful consideration. These factors call for a consolidated investment strategy rather than a scattered country-specific investment focus across the continent.

Given the scattered nature of the opportunities in the solar PV value chain in Africa, we recommend a regionalized solar PV policy and strategy that consolidates the scattered mineral resources, latent productive capabilities, and limited investments for a continental solar PV agenda. Given that the prospects of one African country developing, integrating or upgrading in a solar PV manufacturing chain may be far-fetched, there is a need to consolidate the pockets of opportunities for a regional solar value chain strategy. Among other things, this will involve linking the countries that export the requisite key minerals and have emerging and revealed related technological capabilities in solar PV. In doing so, existing capacities and experiences in African countries such as Morocco, South Africa, and Egypt in the deployment of CSP technologies, for instance, need to be leveraged for a continental agenda. The experiences of Morocco, with its large corporations, mega-project management, and finance, and a robust regulatory framework could also be leveraged to diversify into solar PV production segments.

For Africa to avoid the solar PV manufacturing mirage and successfully 'link up', 'break into,' 'link back,' and 'keep pace' with and thrive in the global solar PV technology supply chain, a regionalized solar PV industrial strategy is imperative. However, we recognize that this regional approach is complex, given geopolitical interests at play. Hence, charting this new future for a regionalized solar PV manufacturing strategy in Africa will require the role of regional institutions and organizations, especially the African Union, African Development Bank, The African Continental Free Trade Area Secretariat, and Afreximbank cannot be overemphasized. While national governments can provide strategic support through direct and indirect interventions on both supply and demand sides needed to crowd-in resources (minerals, capabilities, and investments), regional organizations are critical in fostering the political, economic, social, and financial integration needed for an effective regionalized solar PV manufacturing strategy. The role of the African Minerals Development Centre, for instance, in coordinating and conducting advanced and systematic geological mapping6 of Africa's natural resources would be a critical first step in dispelling the myth about Africa's prospects in building a solar PV manufacturing value chain.

6 The issue of lack of basic geological mapping or poor maps in Africa is emphasised in the Africa Mining Vision 2009 (page 15). Link: https://au.int/en/documents/20100212/africa-mining-vision-amv

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Appendices

APPENDIX A

Cadmium telluride (CdTe) thin film solar is more popular in the United States of America where CdTe cells alone accounted for 29 % of the country's utility-scale PV and ~19% of all U.S. PV systems built in 2021 (Feldman et al., 2021). The technology uses CdTe in a thin semiconductor layer designed to absorb and convert solar radiation into electricity. Accordingly, the key feedstock to the technology is CdTe - a stable crystalline compound formed from cadmium and tellurium. Cadmium occurs as a minor component in most zinc ores and is a byproduct of zinc production. It is a relatively rare metal present in the Earth's crust. Tellurium (Te) on the other hand typically Te is almost exclusively obtained as a by-product of copper refining, with smaller amounts from lead and gold production (Goldfarb, 2014). The production of CdTe solar cells consumes 40% of global tellurium output (Makuei & Senanayake, 2018)

There are currently different types of CdTe based-solar cells exist, albeit CdTe based-solar cells consisting of a p-n heterojunction structure is the most common. Nevertheless, the structure of the solar cells of all types of CdTe based-solar cells are similar and are fabricated considering the superstrate structure (Arce-Plaza et al., 2018; Scarpulla et al., 2022). In general, the fabrication process of CdTe based-solar cells starts by extracting and refining specific minerals such as the key feedstocks. It then proceeds to deposit a series of thin layers including Transparent Conducting Oxide, cadmium sulfide, absorber layer, back contact, and rear conductor on a substrate on glass.7 The current deposition techniques in this regard include sputtering, close spaced vapor transport, chemical spray pyrolysis, and electrodeposition (Arce-Plaza et al., 2018). Finally, the solar cells are delimited by laser scribing or etching before being encapsulated, framed, and covered (IEA, 2022). To achieve long-term reliability with minimized degradation, a second piece of glass and edge seals hermetically encapsulate the module for most commercial modules (Scarpulla et al., 2022).

In general, the CdTe thin film solar is currently the only technology of thin film that has lower costs than conventional crystalline silicon solar cells. CdTe thin-film solar cells can be manufactured quickly and inexpensively, providing an alternative to conventional silicon-based technologies. It also possesses good electronic property favorable for solar cells action: it has an ideal direct band gap ~1.5 eV which corresponds to the optimal theoretical value for the use of the solar spectrum (Sundaram et al., 2018). However, these gains come at a cost associated to the toxicity of the feedstock materials which presents occupational health hazards in various processing steps presented by Cd and Te compounds (Fthenakis & Kalogirou, 2018).

7 CdTe-based solar cells have been made on other substrates such as steel or polymers in laboratories, but these approaches have yet to be commercialized.

APPENDIX B

Table 3: **Distribution of global mineral reserves and production for solar PV technologies in Africa**

Material	Reserve	Mine Production
Silicon	NA	Global = 8,800; China = 6,000/ Africa: NA
Aluminum (metric tons)		Global = 69,000; China = 40,000 (smelter production); Global = 77,000; China – 44,000 (yearend capacity) Africa: NA
Antimony (metric tons)	Global >1,800,000; China = 350,000; Russia = 350,000 Africa: NA	Global = 110,000; China = 60,000 Africa: NA
Copper (thousand metric tons)	Global = 890,000; Chile = 190,000; Congo Kinshasa = 31000; Zambia = 19000	Lead mine production: Global = 22,000; Chile = 5,200; Congo Kinshasa = 2,200; Zambia = 770 Refinery production: Global = 26,000; China = 11000; Congo Kinshasa = 1700; Zambia = 350
Glass	NA	NA
Indium (metric tons)	NA	Global = 900; China = 530
Lead (thousand metric tons of contained lead)	Global = 85,000; Australia = 37,000	Global = 4500; China = 2000
Silver (metric tons of contained silver	Global = 550,000; Peru = 98,000	Global = 26,000; Mexico = 6,300
Tin (metric tons of contained tin)	Global = 4,600,000; Indonesia = 800,000; Congo Kinshasa = 130,000; Nigeria = NA; Rwanda = NA	Global = 310,000; China = 95,000; Congo Kinshasa = 20,000; Nigeria = 1,700; Rwanda = 2,200
Boron (thousand metric tons)	Türkiye, refined borates =1,200,000; Russia, datolite ore = 40,000; United States = 40,000	Chile, ulexite = 300; China, boric oxide equivalent = 300; Türkiye, refined borates = 1,700
Zinc (thousand metric tons of contained zinc)	Global = 210,000; Australia = 66,000	Global = 13,000; China = 4,200

Note: NA – Not available

APPENDIX C

To identify African countries exporting the raw materials for crystalline silicon solar PV technology, we recur to the BACI-CEPII trade data. The data tracks the export activities of countries at the 6-digit harmonized system (HS) classification. Importantly, it contains information on the values of exports and the direction of the trade activities which we explored to compute the export shares of the raw material. For our analysis, we use the HS 17 version of the data and average across the five-year period (i.e., 2017-2021) of which the dataset is available. We then used appropriate concordance table to map the data to the United Nation Broad Economic Categories (UN BEC) Revision 4, to isolate intermediate products as well as identify HS products that are considered primary and processed intermediate products.8 After this, we manually searched for HS codes with seemingly identical names to those raw material identified in the literature to be key to produce crystalline silicon PV. For this exercise, we recur to the official HS 17 descriptions as provided here: https://unstats.un.org/unsd/classifications/Econ/Structure. The products listed in Table 4 are the result of the search and the products considered in our analysis.

Table 4: **Raw materials for crystalline silicon PV and the corresponding HS 17 codes**

Raw materials	HS 17 code	HS 17 code description
Silicon	281122	Silicon dioxide
	280461	Silicon; containing by weight not less than 99.99% of silicon
Aluminum	2606	Aluminum ores and concentrates
	76	Aluminum and articles thereof
Antimony	261710	Antimony ores and concentrates
	8110	Antimony; articles thereof, including waste and scrap
Copper	2603	Copper ores and concentrates
	74	Copper and articles thereof
Tin	2609	Tin ores and concentrates
	80	Tin; articles thereof
Glass	70	Glass and glassware
Molybdenum	2613	Molybdenum ores and concentrates
	8102	Molybdenum; articles thereof, including waste and scrap
Indium	811292	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium; articles thereof, unwrought, including waste and scrap, powders
	811299	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium; articles thereof, other than unwrought including waste, scrap, and powders
Lead	2607	Lead ores and concentrate
	2824	Lead oxides; red lead and orange lead
	78	Lead and articles thereof

8 We source these concordance table from: https://unstats.un.org/unsd/classifications/Econ. Further, our definition and classification of intermediates, including primary and processed intermediates follows the UN classification which can be accessed here: https://unstats.un.org/wiki/display/comtrade/Intermediate+Goods+in+Trade+Statistics

Raw materials	HS 17 code	HS 17 code description
Silver	284321	Silver compounds; silver nitrates
	284329	Silver compounds: excluding silver nitrates
	7106	Silver (including silver plated with gold or platinum); unwrought or in semi-manufactured forms, or in powder form
Zinc	2608	Zinc ores and concentrates
	2817	Zinc; oxide and peroxide
	79	Zinc and articles thereof

APPENDIX D

As noted earlier, our data is at the 6-digit HS 17. To compute the RCA, therefore, we first need to build a crosswalk from the HS to the ISIC. For this exercise we use the ISIC Revision 4 which has a precise categorization of sub-sectors that could be considered to embody the semiconductor and electronics sectors.9 Unfortunately, we did not find an existing concordance table that maps 6-digit HS 17 product to ISIC Revision 4. Hence, we manually build a crosswalk using existing concordance table that maps 6-digit HS17 to CPC Ver. 2.1 and CPC Ver. 2.1 to ISIC Revision 4.10

For the semiconductor and electronics sectors, we focus on two 2-digit ISIC Revision 4 to identify ten 4-digit subsectors we consider appropriate for the analysis. The two 2-digit ISIC Revision 4 include:

- 26: Computer and electronic product manufacturing
- 27: Manufacture of electrical equipment

In general, sector 26 draws together the manufacture of electronic products such as semiconductors and integrated circuits, electronic capacitors, connectors, and resistors, printed circuit boards, computers and computer peripherals, consumer electronic products, communications equipment, electronic instruments, etc. Sector 27, on the other hand, draws together a range of electrical (and some nonelectric) equipment used in electricity distribution and heavy electrical applications such as electric motors and generators, electrical distribution transformers and capacitors, batteries, electrical wiring devices, lighting equipment, and domestic appliances.

Table 5 lists and describes the subsectors under sectors 26 and 27. The grey shaded boxes indicate the ten sub-sectors that we considered to be part of the semiconductor and electronics industry. This comprises i) all the 4-digit subsectors under sector 26, except subsector 2652 and ii) two subsectors under sector 27 including subsector 2710 and 2720. We dropped subsector 2652 because it focuses on the manufacturing of watches and clocks which do not entail the level of technological sophistication needed for solar PV technology. The manufacturing process and material input are also not closely interrelated. We consider only two subsectors (2710 and 2720) under sector 27 because the others focus largely on electric distribution cables and wiring devices that do not match the technicality required for solar PV manufacturing.

By definition, two subsectors 2740 and 2750,

Table 5: **Description of the 4-digit ISIC R4**

2-digit ISIC R4	4-digit ISIC R4	Description of the 4-digit ISIC R4
26	2610	Manufacture of electronic components
	2620	Manufacture of computers and peripheral equipment
	2630	Manufacture of communication equipment
	2640	Manufacture of consumer electronics
	2651	Manufacture of measuring, testing, navigating and control equipment
	2652	Manufacture of watches and clocks
	2660	Manufacture of irradiation, electromedical, and electrotherapeutic equipment
	2670	Manufacture of optical instruments and photographic equipment
	2680	Manufacture of magnetic and optical media

9 Further description on ISIC Revision 4 can be found here: https://unstats.un.org/unsd/classifications/Econ/Structure/Detail/EN/27/C

10 We source these concordance table from: https://unstats.un.org/unsd/classifications/Econ

Raw materials	HS 17 code	HS 17 code description
27	2710	Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus
	2720	Manufacture of batteries and accumulators
	2731	Manufacture of fiber optic cables
	2732	Manufacture of other electronic and electric wires and cables
	2733	Manufacture of wiring devices
	2740	Manufacture of electric lighting equipment
	2750	Manufacture of domestic appliances
	2790	Manufacture of other electrical equipment

appear necessary to be considered. However, upon careful examination, 2740 includes manufacture of electric light bulbs and tubes, electric lighting fixtures and lighting fixture components (except current-carrying wiring devices). 2750, on the other hand, includes the manufacture of small electric appliances such as household-type fans, household-type vacuum cleaners, household-type cooking appliances, etc. As it is obvious, these electronics are less technologically complex, and their material inputs are apart from those of solar PV technology. Hence, we also consider them as unrelated technology and therefore drop them.

In what follows, we compute the Revealed Comparative Advantage (RCA) at the 4-digit ISIC Revision 4 as follows:

$$RCA_j^i = \frac{\frac{X_j^i}{X^i}}{\frac{X_j}{X}}$$

Where ***i*** denotes country and ***j*** denotes the 4-digit ISIC Revision 4, X_j^i is country *i*'s export from subsector *j* and $X^i = \sum_j X_j^i$ is country *i*'s total export from its economy. Where the world is defined by all the countries in the BACI-CEPII dataset, is the world's exports from subsector X_j and ***j*** is the world's total export.

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