Building a Regional Solar PV Value Chain in SADC Region

Insights from China

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by

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Executive Summary

This thesis examines how the Southern African Development Community (SADC) can build a regional solar photovoltaic (PV) value chain, drawing lessons from China's experience.

Although solar energy has become much cheaper—its cost falling by 85% between 2009 and 2023—SADC has not yet fully tapped into its potential. Despite abundant sunlight and mineral resources, the region still lags behind in PV deployment. One of the key reasons is that China dominates almost every stage of the global PV value chain, making it difficult for other regions to compete. For SADC, regionalizing the PV value chain could be a way forward, with mineral-rich countries like the DRC and Zambia supporting upstream supply and South Africa leading in manufacturing.

More background informations being explored in chapter 2. Dig deeper the current situation of solar PV value chain, the prospects of PV technology and its challenges in SADC region, and an overview of PV value chain integration effort in the region. This background information helps the reader to better understand the current state of PV technology, particularly with SADC on it. Then, in chapter 3, a multilayer analytical framework was introduced as an approach for a regionalizing PV value chain. The chapter incorporates the Technological Innovation System (TIS) approach to analyze the development and diffusion of PV technology; design factors in the solar PV value chain; regional integration theories; and the driving forces that including institutional contexts. Further, this framework is being used to guide the analysis process of this research.

The study combines socio-technical analysis with an institutional perspective to explore this opportunity. It uses the Technological Innovation System (TIS) approach, design factors for PV manufacturing, and regional integration theories to structure the analysis. Data was gathered mainly through document review, coding of PV innovation activities, and a small set of interviews, which explored in chapter 4.

The result and analysis of the two case studies are depicted in chapter 5 and chapter 6. It assesses the performance of PV innovation system, detailing the design factors in supporting PV manufacturing development, and the institutional roles within the process. China's success came from strong government coordination, investment in infrastructure, and a strategy that built local capacity step by step until the country captured the full value chain. In contrast, SADC's progress is fragmented, with wide differences in country-level innovation capacity and institutional support. Considering the innovation performance, the country competitiveness, and institutional context, a design for regionalizing solar PV value chain in SADC region is presented in chapter 8.

Whereas, chapter 7 two case studies are compared. The findings suggest that SADC could benefit from adopting coordinated regional strategies, building domestic capabilities where entry barriers are lower, developing stronger financial ecosystems, and investing in integrated infrastructure. These lessons are translated into design options for regionalizing the PV value chain in SADC. Finally, further discussion on the result from this research, the implication to the theory, and future research recommendation is explored in chapter 8. Then it closes with a conclusion in chapter 9.

In closing, this research offers a starting point for how SADC can move from a fragmented, import-dependent PV market toward a competitive and sustainable regional integration. While further feasibility studies are still needed, the study highlights concrete pathways for turning the region's resources into long-term solar leadership.

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Abbreviations

Abbreviation	Definition
AfCFTA	African Continental Free Trade Area
AfDB	African Development Bank
AU	African Union
BRI	Belt and Road Initiative
CAS	Chinese Academy of Sciences
CDB	China Development Bank
CdTe	Cadmium Telluride
CPG	Chinese Central People's Government
CPS	Concentrating Photovoltaic System
CSP	Concentrated Solar Power
CZTS	Copper Zinc Tin Sulfide
DRC	Democratic Republic of Congo
DSSC	Dye-sensitive Solar Cell
EPC	Engineering, Procurement and Construction
EU	European Union
EVA	Ethylene Vinyl Acetate
FDI	Foreign Direct Investment
FIT	Feed-in Tariff
FYI	Five-Year Plan
GEF	Global Environment Facility
GHG	Greenhouse Gas
GVC	Global Value Chain
IPP	Independent Power Producer
IS	Innovation System
ISSB	International Sustainability Standards Board
LPI	Logistics Performance Index
LRE-BRE	Lesotho Renewable Energy-Based Rural Electrification
NDC	Nationally Determined Contribution
NDRC	National Development and Reform Commission
NGO	Non-Governmental Organization
NSTC	National Scientific and Technological Commission
OPV	Organic Photovoltaic
PV	Photovoltaic
PGM	Platinum Group Metal
QDPV	Colloidal Quantum Dot Photovoltaic
REC	Regional Economic Community
REEESAP	Renewable Energy and Energy Efficiency Strategy and Action Plan
RE IPPPP	Renewable Energy Independent Power Producers' Procurement Programme
RIO	Regional International Organization
RIT	Regional Intergration Theory
SACREEE	SADC Centre for Renewable Energy and Energy Efficiency
SADC	Southern African Development Community
SADCC	Southern African Development Coordination Conference
SAPP	Southern African Power Pool
SAREM	South African Renewable Energy Masterplan
SES	Strategic Emerging Sectors
SHS	Solar Home Systems

Abbreviation	Definition
STA	Solar Thermoelectricity System
TIS	Technology Innovation System
TNA	Technology Needs Assessment
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
WTO	World Trade of Organization

1
Introduction

1.1. Background

Net greenhouse gas (GHG) emissions have increased since 2010 in all major sectors worldwide, with the energy supply sector contributing the highest share, about 34% of total emissions in 2019. In response, international agreements such as Paris Agreement agreed to limit global temperature rise to below 2^{o}C, with ideally 1.5^{o}C. As of September 2019, 50 African countries, representing 92% of the continent had ratified the Paris Agreement through Nationally Determined Contributions (NDCs), with a strong focus on renewable energy initiatives as part of climate mitigation and adaptation strategies (AMCEN. et al., 2019).

Among several mitigation options to reduce GHG emissions in energy sector, IPCC (2022) estimates that solar energy potentially contributes to the highest reduction reaching to over 4 $GtCO_2{}^{eq}$ per year by 2030. Global policy supports combined with tailored investments, have helped in reducing the unit cost of solar energy by 85%. This has contributed to a rapid expansion in its deployment, resulting in a more than tenfold increase in some regions between 2010 and 2019. There are various solar technologies available today, each operating on different principles and offering unique benefits. These include solar photovoltaics (PV), concentrating photovoltaic systems (CPS), dye-sensitive solar cell (DSSC), solar thermoelectricity system (STA) and concentrated solar power (CSP). Among them, solar PV and CSP are now the most mature technologies (Chu & Meisen, 2011). This research will emphasize only on solar PV technology.

According to IRENA (2024), the global installed capacity for solar PV grew by 73% in 2023 alone. This growth is largely attributed to a 96% drop in module prices between 2009 and 2023 that was driven by improvements in module efficiency, increased manufacturing economies of scale and vertical integration of the supply chain, optimization in manufacturing, and reductions in materials intensity. However, despite the abundant solar resource, Africa has not kept pace with global deployment trends.

Ndubuisi and Avenyo (2024) suggest that African countries have two key opportunities to leverage the growing trends in solar PV technology: *first*, through their vast land and abundant sunlight for solar PV deployment; and *second*, through their wealth of minerals essential to solar PV technology for resource-led (solar PV) industrialization. Ndubuisi and Avenyo (2024) also highlight the need for African countries to produce solar PV technology within the continent. In Southern Africa, countries like the Democratic Republic of Congo (DRC) and Zambia hold significant reserves of minerals required to produce solar PV, such as cobalt and tin, positioning them at the foundation of the solar PV supply chain. Yet, these countries have the prevalence of exporting the raw materials in primary or processed intermediate form, while, the continent heavily depends on imported solar technologies, indicating not enough manufacturing capacity to absorb the mineral supply (Boakye & Ofori, 2022; Ndubuisi & Avenyo, 2024). On the other hand, South Africa is known to have a strong manufacturing sector and a strong regulatory framework in renewable energy, which opened up more investments opportunity for solar PV manufacturing development (Shopia. et al., 2024). This contrast illustrates the fragmented production capacities and capabilities across the continent.

This imbalance is intensified by the highly concentrated global solar PV value chain. China dominates the supply of critical materials, module manufacturing, installed capacity, and recycling capacity, controlling over 80% of the production of PV main components and over 30% of installed capacity worldwide (Chadly et al., 2024). With China dominating the supply of minerals, it is almost impossible for other countries to guaranteeing a fixed availability of raw materials which poses a high risk to global solar PV production associated with insufficient production capacity, geopolitical concerns, and market price dynamics (Chadly et al., 2024; Karali & Shah, 2022). In short, China's domination has created a strong barrier to entry for other countries, particularly those in the Global South, including Southern African countries (Ndubuisi & Avenyo, 2024).

1.2. Scientific Knowledge Gap

Relevant articles and policy papers on Africa's solar PV industry were reviewed. One exception is Andreoni and Avenyo (2023), which does not focus directly on solar PV but examines mineral-based manufacturing in African countries, including minerals like copper and cobalt that are important for the PV value chain. Although these minerals are valuable for solar PV production, many countries in the region face challenges due to limited production capacity to process them into higher value-added products.

Among the reviewed literature, Davy et al. (2024) provides a valuable perspective by highlighting a gap in the current debate on renewable electrification in late industrializing economies. While much of the discourse has focused on improved electricity access and climate mitigation, less attention has been given to the opportunities for localization and the development of green industrial activities, such as solar PV manufacturing. Through a case study of a local module manufacturer in Kenya, Davy et al. (2024) found the factors that affecting its competitive advantage and survival, including its linkages and knowledge transfer from upstream industries, targeting niche market through strong relationships with downstream partners, close proximity to customers that allowed for better warranties and aftersales services which Chinese suppliers typically do not provide, as well as the provision of complementary and high value-added services, such as Engineering, Producerement and Construction (EPC) services.

Moreover, Malima et al. (2024) found that local participation in the PV manufacturing chain including the product design, engineering, core component manufacturing and equipment assembly like solar PV modules remains limited in the off-grid solar market. The paper's highlighting the need to build local capacity in auxiliary services for the deployment value chain and to attract more investment in large-scale solar systems to deepen local content. Additionally, Nygaard et al. (2017) studied the diffusion of solar PV technology under the Technology Needs Assessment (TNA) projects, including one in Zambia.The research also highlighting the local panel assembly and system component production as key opportunities to build national innovation systems.

Despite encouraging findings on the potential for localizing solar PV production, the reviewed papers also highlight significant challenges from both the perspectives of manufacturers and national-level strategies. At the country level, key obstacles include high interest rates and limited capital, limited research and development activities at the national level, and the absence of supportive policies and regulatory frameworks (Davy et al., 2024; Nygaard et al., 2017). From the manufacturers' perspectives, challenges include intense competitions from low-cost import products, low-quality local products due to poorly enforced standards and low level of technical skills, low-value locally manufactured components that weakens supply linkages, as well as high upfront and running costs especially in polysilicon productions (Davy et al., 2024; Malima et al., 2024; Ndubuisi & Avenyo, 2024; Nygaard et al., 2017).

Due to that complexities and challenges in solar PV value chain, it is necessary for understanding the dynamics of the PV innovation system. Supporting local production is challenging and requires a multi-sector approach, not just from the energy sector, but also involving finance, innovation, firm learning, and niche development. While each country has scattered nature of opportunity in localizing solar PV productions, Ndubuisi and Avenyo (2024) suggest a regionalized approach for connecting the countries based on their mineral endowement and emerging technological capabilities. Support of regional institutions like African Union (AU), African Development Bank (AfDB), and African Continental Free Trade Area (AfCFTA) are required to integrate the value chain (Boakye & Ofori, 2022; Ndubuisi & Avenyo, 2024).

While the regionalization of the solar PV value chain in Africa is widely acknowledged as important, there remains a lack of concrete guidance on how to effectively operationalize this strategy. Existing literature often overlooks the roles of key institutions, such as regional bodies, international organizations, and foreign direct investment (FDI), in supporting regionalization efforts. Additionally, studies specifically focused on the potential for localizing PV production within the SADC region as one entity are still limited, with most of the studies concentrated in the South Africa and in the PV deployment phase (Baker & Sovacool, 2017; Craig et al., 2019; Mutumbi et al., 2024; Semelane et al., 2021). Given the scarcity of research on PV value chains in SADC context, an overview of solar PV status in the region will be presented in chapter 2. To better understand the current research landscape and identify potential areas for further investigation, the research gap in the regionalization of the PV value chain is summarized in Table 1.1.

Table 1.1: Research Gap in Regionalizing Solar PV Value Chain in Africa

Authors	Research Gap
Nygaard et al. (2017)	Historical data and deeper exploration of the socio-economic parameters influencing PV diffusion across different countries and market segment in Africa is needed. The paper concentrates on identifying barriers and government measures across several African countries, yet still lacks a value chain lens for manufacturing localization.
Davy et al. (2024)	The dynamics of solar PV manufacturing value chain in Africa indicating a need for further exploration in a broader population of representative firms (to be more generalizable). The paper focuses on enabling factors for local PV manufacturing (one company case study) to gain several advantages, yet does not address how these lessons might scale regionally or across different value chain segment.
Malima et al. (2024)	Limiting the generalizability to other African countries and indication of a gap in understanding how the linkage between FDI and knowledge spillover affecting the competitiveness and capabilities of domestic firms. The paper recommends building the capacity of local solar companies to engage in donwstream activities, yet still miss the actionable strategies to make this recommendation happen.
Andreoni and Avenyo (2023)	Lack of practical local content requirements in African countries, which may hinder the technological and operational needs of mining companies, suggesting a gap in policy effectiveness. While the paper offers a framework for leveraging critical minerals, the paper focuses more broadly on medium-high technology industrialization and lacks specific operationalization strategies for regional solar PV value chains.
Ndubuisi and Avenyo (2024)	Need for further exploration of strategies to overcome the barriers of market concentration and strong entry into global solar PV manufacturing value chain, suggesting a regionalized solar PV policy and strategy. While it suggests a regionalization solar PV value chain, the paper still miss the clear directions of how to operationalize the regionalization strategy.
Boakye and Ofori (2022)	Current regulatory frameworks that enables business participation in production stages are still lack, thus need to explore the Africa's competitiveness and more comprehensive analysis in the solar PV value chain analysis.

Source: Author's compilation

1.3. Problem Statement

As mentioned above, African countries, including Southern African Development Community (SADC) region, hold significant potential for localizing solar PV production. However, due to its fragmented resources and technological capabilities, following with a strong barrier to enter the global PV value chain, achieving similar outcomes and competing with China at national level may be difficult. Rather than being separate strategies, regionalization can serve as an enabler of localization by pooling resources, coordinating efforts, and overcoming barriers in the solar PV value chain.

While existing literatures have explored the potential of solar PV productions in the local basis alongside with its challenges, there remains a gap in understanding how regional integration can enable the region to seize their opportunities across different stage of the value chain. The SADC region brings together countries with complementary capabilities. For instance, mineral-rich nations such as DRC and Zambia can anchor the upstream supply of raw materials, while South Africa with its relatively advanced industrial bases and growing energy demand can support the development of PV manufacturing.

Such regional approach is inherently complex, due to varying national interests, geopolitical dynamics, and the involvement of multinational institutions. Therefore, it is necessary to understand the challenges of integrating solar PV value chain from systemic lens. Successful regionalization depends not only on drafting good policies, but also on fostering a culture of cooperation, mutual benefit, and institutional learning across countries.Therefore, understanding the role of institutions both as formal rules and informal norms is also essential for advancing regionalization efforts. Nevertheless, China's experience can offers valuable lessons. It demonstrates that integrated value chain development by combining resources endowment, manufacturing capacity, domestic demand stimulation, and strong policy coordination can transform an energy sector.

1.4. Research Objective

This research intends to propose strategic institutional interventions to develop and integrate regional solar PV value chains in SADC region. This will be done by identifying the socio-technical factors alongside the actors and institutions involved in two case studies: solar PV development in China and the SADC region. Additionally, it will extract valuable lessons from China's experience to shape the strategic interventions in the institutions within SADC region to integrate its PV value chain.

The findings from this research potentially contribute to the theory surrounding the regional integration and solar PV value chain, offering comprehensive insights into the complexity of integrating national interests and multinational institutions. Practically, this study provides actionable guidelines for SADC region, aiming to leverage the integration of solar PV value chain within the region.

1.5. Research Question

The main research question would be ”What are the strategic interventions for the SADC region to develop a regional solar PV value chain?”

The research will break down the main research question into the following sub-research questions:

- SRQ1: How did China develop and maintain its leadership in the global solar PV value chain?
- SRQ2: What are the socio-technical factors that trigger and hamper the integration of solar PV value chains in the SADC region?
- SRQ3: What lessons can be drawn from Chinese case to foster the development and integration of regional solar PV value chain in the SADC region case?

2
Background Information

2.1. What are Regional and Global Value Chains?

Antràs (2020) describes a Global Value Chain (GVC) as a series of stages involved in producing a product or service that is sold to consumers, with each stage adding value, and with at leas two stages being produced in different countries. In other words, it is a production process that embodies value added from at least two countries. GVCs have transformed production by enabling companies/organizations to offshore and outsource different stages of their operations across multiple countries for greater efficiency. This fragmentation not only optimizes costs but also allows innovation and other activities to be geographically dispersed and independent from the core production process (Ambos et al., 2021).

Gereffi and Fernandez-Stark (2016) suggested that recent evidance indicates a shift toward the regionalization of value chains, driven by the rising influence of large emerging economies and the expantion of regional trade agreement. Regional trade agreements or trade agreements more broadly, are highly effective in reducing trade barriers between participating countries. Indeed, GVCs are particularly more active among nations that have signed regional trade agreements as they facilitate smoother cross-border trade and collaboration (Antràs, 2020). As Suder et al. (2015) stated that the interconnectedness of regional trade and production networks plays a crucial role in enhancing national economic growth, fostering regional stability and facilitating the expansion of production on a global scale.

2.2. Solar PV Value Chain

Solar PV is one of the most mature technologies under the solar energy domain that currently available. Solar energy falls on the surface of the earth at a rate of 120 petawatts, meaning that the total sunlight hitting the planet in a single day could generate enough energy to meet global demand for more than 20 years. Other solar technology that currently available including concentrated photovoltaic systems, dye sensitized solar cell, solar thermoelectricity system, and concentrated solar power (Chu & Meisen, 2011).

The technology simply works when photovoltaic panels absorb photons from the sunlight using its semiconducting material, the electrons are then move and generate electric power (Chadly et al., 2024). Generally, there are two basic categories of solar PV technologies including silicon PV (wafer-based cells) and thin-film PV (Chadly et al., 2024; Jean et al., 2015). While silicon PV dominates the PV market today, alternative technologies such as other type of materials in wafer-based and thin-film PVs are evolving rapidly, yet it is also important to note that the road to market and large-scale deployment is invariably long (Jean et al., 2015). Further, the classifications are explained below:

- **wafer-based cells**, which are made on semiconducting wafers and do not require an additional substrate but are usually covered with glass for stability and protection (Jean et al., 2015). There are three primary wafer-based technologies exist today, including crystalline silicon (c-Si), gallium arsenide (GaAs), and III-V multijunction (MJ). Acccording to IEA (2022), the crystalline silicon (c-Si) modules constitute more than 95% of current global production capacity and are the most mature of all PV technologies.
- **thin-film cells**, which are formed by depositing semiconducting films onto substrates such as glass, plastic, or metal, which may reduce material usage and manufacturing capital expense (Jean et al., 2015). However, according to Ndubuisi and Avenyo (2024), many thin-film solar

cells have shorter operational lifetimes and larger degradation rates than the c-Si wafer-based solar cells, in accelerated life testing. Initial capital expenditure for thin-film production equipment is also relatively high compared to that c-Si, with unstandardized production equipment. The thin-film PVs are categorized into two, the commercial thin-film which based on conventional inorganic semiconductors and the emerging thin-film which based on nanostructured materials. Among the commercial thin-film PV technologies, cadmium telluride (CdTe) is the leading thin-film technology with a global PV market share of 5% (IEA, 2022) and a thin-film market share of 56% in 2013 (Jean et al., 2015). While the emerging technologies, such as copper zinc tin sulfide (CZTS), perovskite solar cells, dye-sensitized solar cells (DSSCs), organic photovoltaics (OPV), and colloidal quantum dot photovoltaics (QDPV) have not yet been deployed at scale.

IEA (2022) spans the solar PV supply chains into five main segments of the manufacturing process, consisting polysilicon, ingot, wafer, cell and panel/module. In 2021, the world was making far more solar panels, specifically the wafers and cells inside them, than were actually needed. However, there was a shortage of polysilicon, the main raw material used to make those parts. Even though the rest of the supply chain had extra capacity, the limited supply of polysilicon created a bottleneck, causing a tight global supplies and increased price of polysilicon. Shopia. et al. (2024) categorizes the PV value chain into three stages including upstream, midstream and downstream. In the *upstream stage*, the process starts with extracting and refining raw materials, mainly silica (SiO□), found in sources like quartzite, quartz pebbles, and quartz veins. This silica is purified into high-purity polysilicon (with a purity level of 6–13N). The purified polysilicon is then melted, formed into large solid blocks called ingots, and sliced into thin wafers for the next stage of production (IEA, 2022; Shopia. et al., 2024). Moving on to *midstream stage*, the resulted wafers undergo various processes to transform them into solar cells. The individual cell are then assembled to produce solar modules, which is the cornerstone of the solar energy technology as it includes the solar cells that transforms sunlight into electricity (Shopia. et al., 2024). Lastly, the *downstream stage* consist of integrating the solar modules into PV system or to use it in various PV application products. PV power systems can range from residential rooftop installations to large-scale utility projects while PV application products range from solar-powered streetlights to portable chargers (Shopia. et al., 2024).

Moreover, to support the main technology in solar PV, Ou et al. (2024) put PV auxiliary materials, PV processing equipment and inverters of PV among the stages of PV value chain. PV auxiliary products such as doping agents, metal contacts, and anti-reflective coatings are often produced from specialized chemical and material companies, that lies under upstream sector (Ou et al., 2024; Shopia. et al., 2024). PV processing equipment or capital equipment production is required for the production of polysilicon, cells, and modules in the PV industry, such as the furnace for polysilicon purification, chemical and gas suppliers, abrasives, and equipment for cutting wafers, pastes, and inks for cells, encapsulation materials for modules, and specialized measurement equipment use in production (F. Zhang & Gallagher, 2016). Following the classification by Ou et al. (2024), this research also categorizes the manufacturing of such machinery and equipment within the midstream sector, given its capital-intensive nature. While inverters are components integrated within the PV system and fall under downstream sector (Ou et al., 2024).

Based on the information above, an overview of the solar PV value chain is drawn in Figure 2.1. While there are two leading solar PV technologies, the c-Si PV and the CdTe PV, this figure depicts more on the silicon solar PV value chain.

To get a better understanding on the process of adding value from silica (SiO2) as raw materials to solar PV system as final product, we will explore the key activities, resources, and capabilities required for every segment. The discussion of the global actors will be fused within every segment.

1. **Upstream**
   Solar PV manufacturing requires metals, metalloids, non-metallic minerals, and polymers as the ***key materials***, which vary across technologies and segments. The majority of a module's weight comes from solar-grade glass, aluminum, and polymers such as EVA, polyolefin, PVDF, PVF or PET (IEA, 2022). The use of selectted materials in c-Si and CdTe solar PV manufacturing can be seen at Table 2.1.

   The manufacturing of solar PV modules requires additional raw materials, such as carbonated

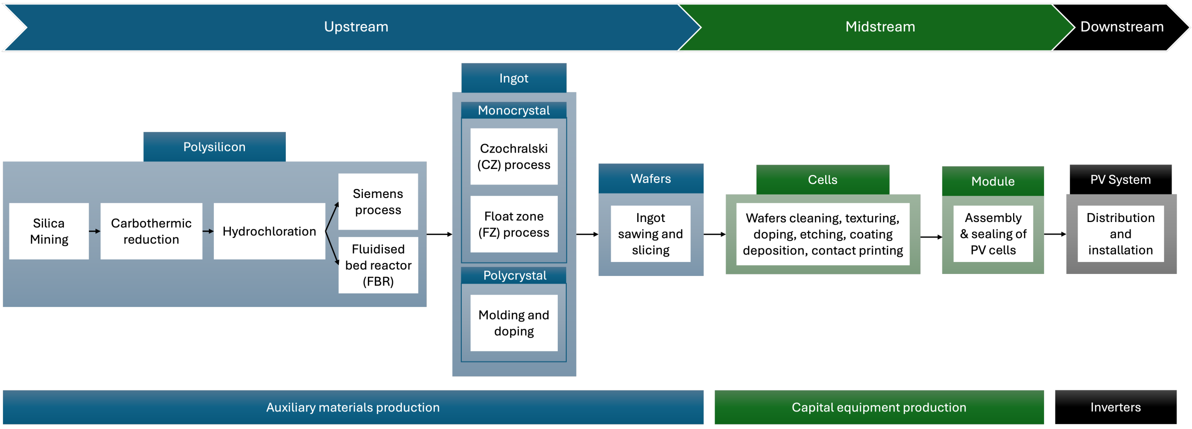

Figure 2.1: An Overview of the Solar PVs' Value Chain
Source: Author's own compilation based on data from IEA (2022), Ou et al. (2024), and Shopia. et al. (2024)

feedstocks materials like coal, woodchips and charcoal for carbothermic reduction of quartz and quartz crucibles for Czochralski process to produce monocrystalline silicon ingots. Demand for these materials will rise following the increasing production capacity of solar PV. It is also important to note that reducing the material intensity of the costly components is essential for lowering production costs and mitigating the impact of volatile commodity prices.

To produce ***polysilicon***, the process starts with the extraction and refinement of raw materials, primarily metallurgical-grade silicon (Mg-si) from quartzite and quartz pebble to produce high-purity polysilicon (IEA, 2022; Shopia. et al., 2024). To melt quartz silica into Mg-si requires a 1700°C arc furnace. Then, there are two different methods to achieve high-purity silicon (6-13N purity), through Siemens chlorination (employed over 90% of polysilicon produced today) or alternatively by a fluidised bed reactor (less energy used but lower-purity silicon). To produce high-purity polysilicon requires simpler and more conventional equipment such as vacuum chambers and melting furnaces, but it has the most CO2-intensive process and uses high-intensive energy due to the high temperature of the heat and lengthy time it needs to melt quartz, extract silicon and refine it to the level of purity required for solar cells. Polysilicon production accounts for 40% of all energy consumed to manufacture solar PV modules, the largest portion of all supply chain segments. Despite its high-intensive energy used, there is an energy and material efficiency in the Siemen process that have significantly improved over the past decade, resulting in nearly 50% energy savings (IEA, 2022).

High-purity silicon resulted from the process above goes to different processes resulting either ***singlecrystalline silicon (sc-Si) ingot*** or ***multicrystallin silicon (mc-Si) ingot***. Cylindrical single crystals are typically grown by Czochralski methods or Float-zone methods, while mc-Si blocks are formed by casting process (IEA, 2022; Jean et al., 2015). According to the 2024 International Technology Roadmap for Photovoltaic (ITRPV), Sc-Si ingots have become the dominant industry standard, accounting for nearly all market share in 2023. Materials like quartz crucibles are needed to run the Czochralski process. Same as polysilicon production process, to create Ingots also require simpler and more conventional equipment. Ingot and polysilicon production together make up two-thirds of total electricity consumption, where it requires high heat temperature for over a period of 100-200 hours. Because those production processes usually require a constant load, therefore co-locating solar PV manufacturing facilities and other industrial consumers of renewable electricity would help reduce electricity costs.

Furthermore, to produce thin ***wafers***, a large ingot is sliced using precise cutting techniques resulting 150-180 μm wafers prior to cell processing (IEA, 2022; Jean et al., 2015; Shopia. et al., 2024). Electricity consumption represents nearly 20% of the total energy usage in ingot and wafer production, making it the second-highest energy-intensive process after polysilicon production. Collectively, polysilicon and ingot/wafer production account for approximately 70% of total investment in solar PV manufacturing, primarily due to their high capital requirements. However,

Table 2.1: Key Materials in c-Si and CdTe solar PV manufacturing

Materials	Shares	Main Uses
c-Si solar PV		
Aluminium	9-12%	Module frame, mounting structure, connectors, back contact, inverters
Antimony	*Tr*	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
Copper	5-12%	Cables, wires, ribbons, inverters
Glass	11-15%	Module cover
Indium	*Tr*	Transparent conducting layer (indium tin oxide—ITO) in silicon heterojunction—SHJ
Lead	<0.05%	Soldering paste and ribbon coating in c-Si modules
Silicon	35-45%	c-Si wafers, in the form of high-purity quartz (HPQ) for crucibles to grow monocrystalline silicone ingots via the Szochralski process
Silver	9-23%	Electronic contacts, silver paste, busbars and soldering
Tin	0.1-0.5%	Solder, ribbon coating in c-Si modules
Zinc	0.03-0.1%	Galvanized steel in mounting structures
CdTe solar PV		
Aluminium	28-37%	Module frame, mounting structure, connectors, inverters
Antimony	*Tr*	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
Cadmium	0.1-0.2%	Absorber layer
Copper	0.3-4%	Cables, wires, ribbons, inverters
Glass	47-54%	Module cover
Indium	*Tr*	Transparent conducting layer (indium tin oxide—ITO)
Molybdenum	*Tr*	Back contact layer
Selenium	*Tr*	Absorber layer in some CdTe cells
Silver	*Tr*	Electronic contacts, silver paste, busbars and soldering
Tellurium	3-6%	Absorber layer (CdTe) and back contact (ZnTe)
Tin	*Tr*	Solder, transparent conducting oxide (indium tin oxide)
Zinc	*Tr*	Galvanized steel in mounting structures, back contact (ZnTe)

Note. Shares of each material over total raw material costs in PV module production. It is important to note that highest share of material cost doesn't mean that the material makes up the highest composition of module's weight. *Tr*: share is detectable but very low.

Source: IEA (2022)

wafer and ingot manufacturing can generate 180-400 jobs, with the higher end of this range occurring in markets with lower capacity per manufacturing plant, which require more labor compare to polysilicon production that only create 50-100 jobs for every 1 GW polysilicon production capacity (IEA, 2022).

China dominating almost all minerals needed for c-Si solar PV production, as well as the polysilicon and wafers production. Countries dominating the world's production of minerals can be seen in Figure 2.2.

In 2021, 85% of polysilicon manufacturing jobs were in China with main importers from Germany, Malaysia, and Japan due to the insufficient domestic production to meet their local demand (IEA, 2022). China also dominating 97% of global wafer production capacity, marked as the most concentrated segment of the solar PV supply chain. Finished wafers were primarily exported to Asia-Pasific countries like Malaysia, Vietnam, Thailand and Korea to be used for solar cells manufacturing. These countries were in turn responsible for over 60% of global cell exports, as China mainly used its own production domestically.

2. **Midstream**
The thin silicon wafers undergo various processes to transform into functional solar ***cells***, depending on the exact cell technology. There are at least 8 steps that are involved for heterojunction cells and 11 steps for TopCON cells. These include cleaning the surface, applying anti-reflective coatings, doping to create positive and negative layers, and adding metal contacts to collect elec-

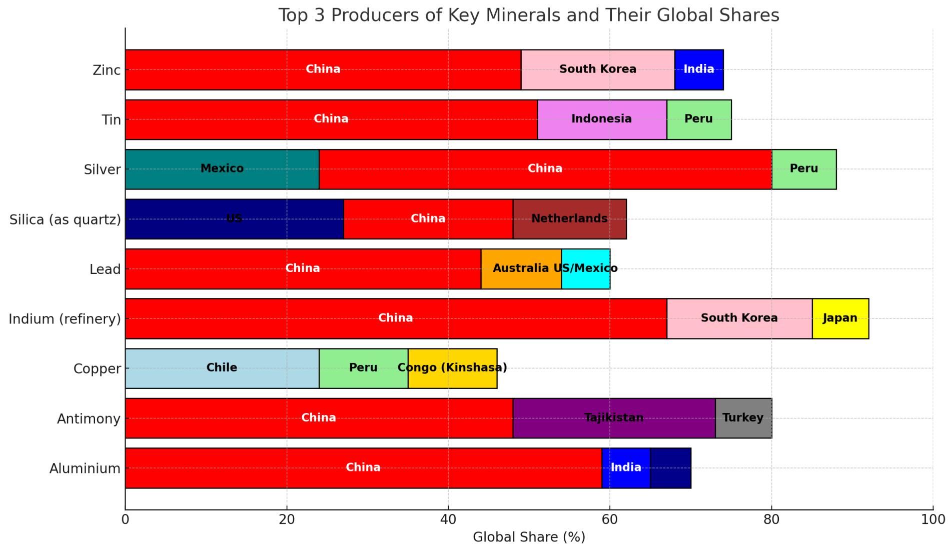

Figure 2.2: Top 3 Producers of Key Minerals
Source: USGS (2022)

tricity (IEA, 2022; Shopia. et al., 2024). A high-efficiency sc-Si variant is the heterojuction with intrinsic thin layer (HIT) technology, which combine n-type sc-Si with thin amorphous silicon films, which reduce interface combination and can increase open-circuit voltages by 5-10%. Multicrystalline silicon (mc-Si) cells, on the other hand, consist of randomly oriented grains (about 1 cm^2 in size), which creates grain boundaries that hinder charge extraction, making them less efficient than sc-Si cells. Record cell efficiencies stand at 25.6% for sc-Si and 20.8% for mc-Si (Jean et al., 2015).

Individual cell clusters are joined together to form a solar ***module***, typically encapsulated with protective materials enhance durability against environmental conditions. This process is knows as the PV module assembly stage. It is the cornerstone of the solar energy technology as it integrates solar cells which responsible for converting sunlight into electricity, along with key components such as the aluminum frame, glass, encapsulant, backsheet, and junction box to ensure functionality and longevity(Shopia. et al., 2024). Since solar cell production requires advanced technology and strict quality control, module assembly lines also depend on highly automated systems with multiple quality testing stages. In terms of energy consumption, cells and modules account for less than one-third of the total, as their manufacturing processes require lower temperatures for drying and cooling, with most electricity used for automated mechanical operations (IEA, 2022).

According to IEA (2022), module assembly requires low investment and minimal expertise, had the highest capacity but lowest utilization. It only requires 3-12-months to deploy cell and module factories in most parts of the world. Low solar cell prices, local sourcing of components, trade restrictions and government support have driven global investments in module assembly. As a result, by 2021, 38 countries had module assembly capabilities, making it the most widespread step in the PV manufacturing process. However, many of these investments were small-scale or remained at the pilot stage, with only 19 countries having an assembly capacity of at least 1 GW.

When it comes to solar cells and modules, Southeast Asia—particularly Vietnam, Malaysia, and Thailand—has significant manufacturing capacity, serving as key alternative of solar cells production hubs outside of China. Cell and module manufacturing capacity is more geographically distributed than that of polysilicon and wafer production, implying fewer competitiveness risks to the global supply chain. Today, Southeast Asia and Korea hold 18% of the global cell market, leaving only 2% of production to the rest of the world. China held 75% of global module manufacturing capacity, following with Vietnam, Malaysia, Korea and India which collectively hold 12% of the world's module production capacity. Although many countries have multi-GW module production capacity, most plants assemble modules from imported parts. For instance, United States, India, and Europe rely on imports from Asia-Pasific for 60-70% of their solar cells supply to produce modules (IEA, 2022).

Moreover, Between 2017 and 2021, global sales of PV manufacturing equipment surged by 80%, surpassing USD 8 billion. Asian countries lead the market, with China contributing nearly half of total sales, while Korea, Chinese Taipei, and Japan collectively account for an additional quarter—reflecting significant growth over the past five years. Approximately 50% of these global sales are attributed to equipment used in converting wafers into solar cells. This process demands high levels of sophistication, precision, and advanced automation, making the associated machinery more costly than that used in other segments of PV manufacturing (IEA, 2022).

3. **Downstream**
Solar modules are integrated into ***PV power systems*** or used in various PV application products. The solar PV system consists of the PV module and other ancillary equipment such as inverters, mounting systems, trackers, and cables that required for the installation of solar PV systems (Shopia. et al., 2024). In Europe, inverter manufacturing represents almost half of all employment in the PV manufacturing sector (Solar Power Europe, 2021), whereas in the United States, approximately 20% of PV manufacturing jobs are associated with racking and mounting systems (IEA, 2022).

As noted by IEA (2022), to align with the IEA Net Zero Scenario, the average annual rate of global solar PV installations must nearly quadruple over the next decade. Solar PV is expected to supply around one-third of global electricity by 2050, a significant increase from just 3% in 2021. However, the IEA projects that existing government policies fall short of driving solar PV demand to the necessary levels. China's contribution to global annual installations rose sharply—from 12% in 2012 to nearly 45% by 2016. Globally, the majority of solar PV employment is concentrated in plant construction and panel installation on residential and commercial buildings, which generates more jobs than the manufacturing segment.

In short, China hosts major production facilities in the upstream, midstream, and downstream stages (Shopia. et al., 2024). As of today, China's share in all segments of solar panels manufacturing exceeds 80%. Additionally, the country is home to the world's 10 top suppliers of solar PV manufacturing equipment. China dominates the mining and processing of critical rare earth elements essential for renewable energy technologies by upholding more than 50% of the global production of each metal, leaving Europe, Asia, and America heavily reliance on its supply for solar and wind technologies (European Comission, 2023; Rabe et al., 2017). China also leads in manufacturing capacity for Modules, Cells, Wafers, and Polysilicon. In 2021, China's production capacity for wafers reached to 98% of global production, following with the production of cells (85%), polysilicon (80%), and modules (75%) (IEA, 2022). Lastly, China is striving to lead the solar PV installation as well. In 2023, China's market for solar PV reached to 63% of the global total, with major capacity increases to 217 GW installations (IRENA, 2024).

2.3. SADC Region: Minerals Endowment and Solar PV Status

This study uses the classification of Regional Economic Communities (RECs) under the AU, focusing on the SADC region. SADC was originally established in 1980 as the Southern African Development Coordination Conference (SADCC), a loose alliance of nine majority-ruled countries in Southern Africa. On August 17, 1992, it was formally transformed from a Coordinating Conference into a Development Community (SADC), gaining legal status as a regional organization. The member states are Angola, Botswana, Comoros, DRC, Lesotho or Kingdom of Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland (currently called as Eswatini or Kingdom of Eswatini) , Tanzania or United Republic of Tanzania, Zambia, and Zimbabwe (www.sadc.int).

Andreoni and Avenyo (2023) mentioned that Africa has most of the critical minerals needed for clean energy manufacturing and has the potential to be a central role in the green energy transition, such as Cobalt, Bauxite, Platinum Group Metals (PGMs) and Chromium. However, historically, the continent has underutilized its natural resource potential, capturing only about 40% of the possible revenue from these assets (UNCTAD, 2024). Africa's reliance on mineral resource exploitation and integration into

GVCs has increased since the mid-1990s, driven by foreign investments in the extractive sector. While this GVC-led model has boosted production and integration, it has primarily resulted in dependence on exporting raw commodities, with minimal domestic value addition and limited advancements in local manufacturing. Consequently, this approach has not delivered the quality growth Africa needs to address its development challenges (Andreoni, 2019) in (Andreoni & Avenyo, 2023).

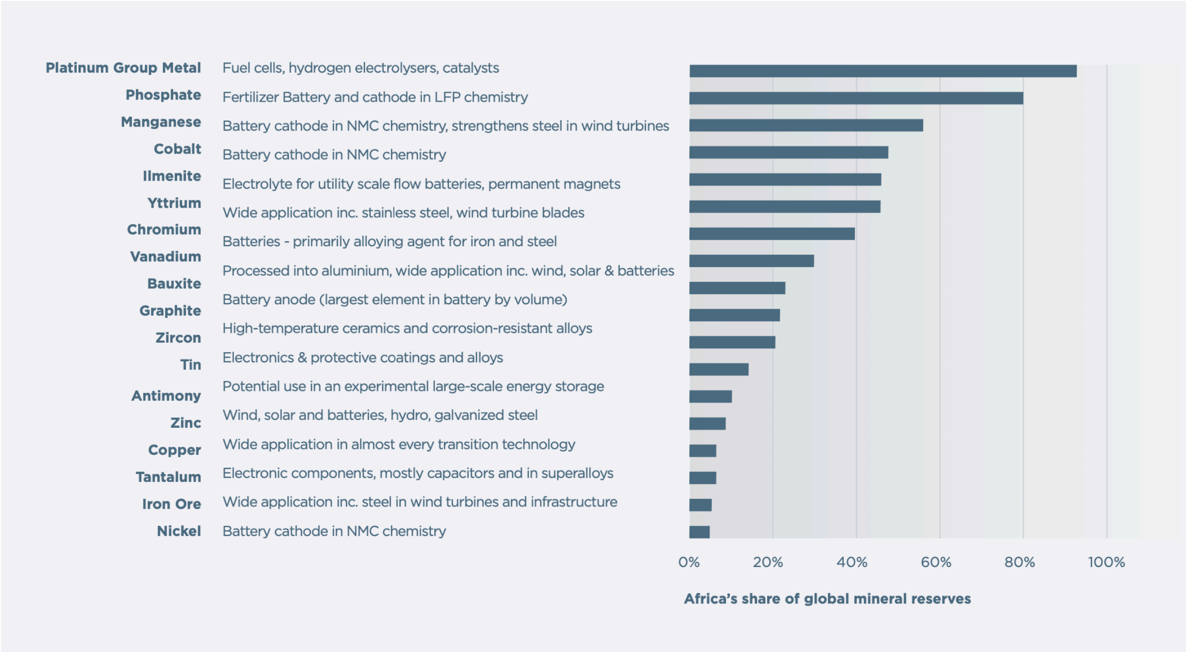

Figure 2.3: Africa's Share of Global Mineral Reserves
Source: Diene et al. (2022)

According to data from Diene et al. (2022), as shown in Figure 2.3, and supported by Ndubuisi and Avenyo (2024), only a few of the minerals needed for solar PV production are currently available and mined within the SADC region. These include bauxite (used to produce aluminium), tin, antimony, zinc, and copper. Mozambique is the fourth-largest bauxite exporter in Africa with 8.870 tons in 2019 (AMDC, 2024a). Copper and Tin are mainly found in the DRC and Zambia, where DRC is one of the global top 3 Copper producers (Ndubuisi & Avenyo, 2024; USGS, 2022). Zambia, South Africa and Namibia also part of the major contributors for copper production and exploration, with main export destinations including China, Switzerland, and India (AMDC, 2024b). Namibia, Botswana, and South Africa are the only three countries in the SADC region that export all 11 key raw materials needed for the production of crystalline silicon (c-Si) based solar PV (Ndubuisi & Avenyo, 2024).

The abundance of solar irradiance is also important to take into a note as a key opportunity for building solar PV value chain in SADC region. Figure 2.4 suggests that SADC has one of the highest solar irradiation in Sub-Saharan Africa. However, so far only 1% of solar energy potential has been tapped (Musasike et al., 2024). Musasike et al. (2024) found that local developers lack the capacity, skills and know-how to deliver the 52.8GW by 2040. Therefore, prefeasibility facilities like early-stage funding programs could play could play a key role in helping the region reach its energy goals and making 53% of the energy mix renewable by 2040.As of 2022, renewable energy made up 28% of Southern Africa's total power capacity, while coal remained the dominant source at 61%. Hydropower is mainly driven by Zambia, Mozambique, and Angola, whereas wind and solar energy are concentrated mostly in South Africa (Ciceu et al., 2025). Despite this imbalance, there are encouraging trends for solar energy. According to Ciceu et al. (2025), solar was the most attractive renewable technology between 2014 and 2023, receiving about two-thirds of all renewable energy investment in the region, with South Africa alone accounting for 86% of that total.

When it comes to local manufacturing of solar PV products, Jadhav et al. (2017) found that there is generally a lack of reliable services and manufacturing capacity in SADC region. Spare parts and skilled technicians for installing and maintaining solar systems are hard to find locally. Moreover, there are

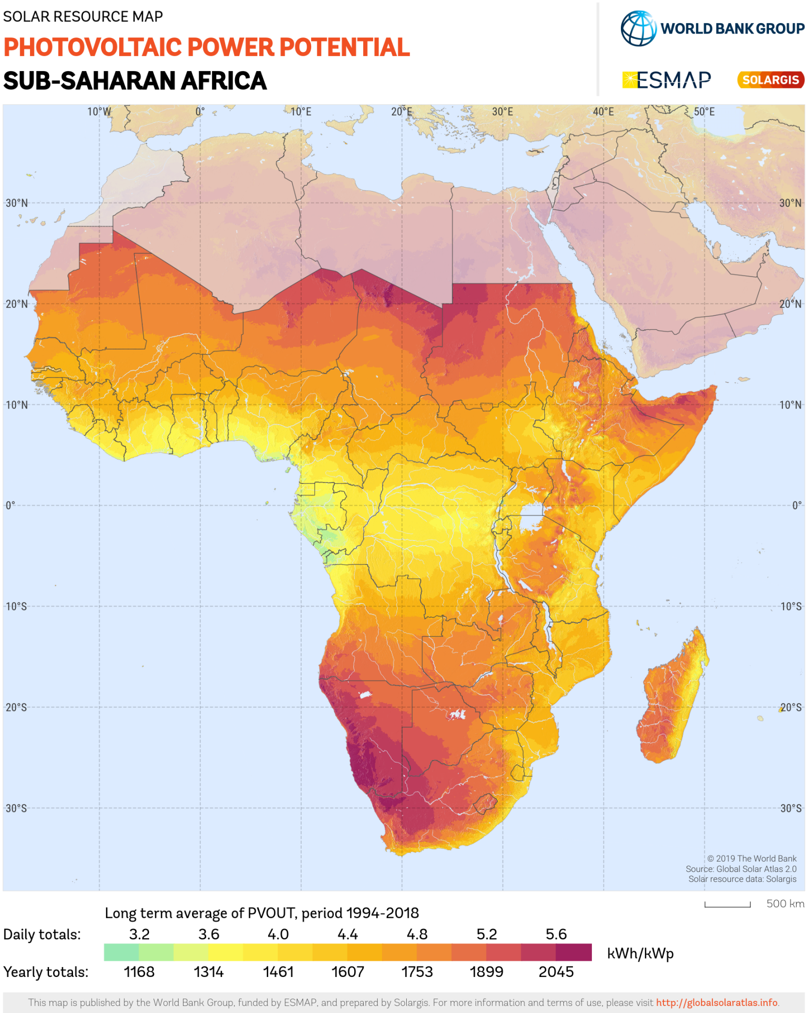

Figure 2.4: Sub-Saharan Africa Photovoltaic Power Potential
Source: https://globalsolaratlas.info

no strong local industries to support the rollout of solar technologies, which leads to heavy reliance on imports that are often costly and sometimes low in quality. This is further supported by UNCTAD (2024), which notes that many African countries face challenges such as weak governance, poor infrastructure, and unstable development financing. These issues make it difficult for them to fully benefit from their natural resources and turn them into long-term economic growth. Additionally, energy poverty and inadequate infrastructure remain significant challenges, hindering the development of a solar PV value chain across African countries, including SADC region (Ndubuisi & Avenyo, 2024).

According to Africa Clean Energy Technical Assistance Facility & World Resources Institute (2021), only a small number of companies in Tanzania and Zambia are involved in assembling off-grid solar panels, highlighting the need for governments to offer more incentives to encourage private sector participation. In South Africa, Semelane et al. (2021) noted that efforts to localize solar PV manufacturing have fallen behind, despite its potential to support a "just energy transition". Additionally, Shopia. et al. (2024) found that South Africa still lacks the capacity to convert their silicon into polysilicon due to the high technological and financial barriers involved. This technology gap, coupled with high investment risks and cost-efficiency concerns, hinders the development of the upstream PV value chain in South Africa.

2.4. Overview of SADC's PV Value Chain Integration Effort

There are still only a few studies that specifically examine the integration of the solar PV value chain within the context of the SADC region. One of the earliest studies on solar energy in the SADC region was conducted by Jadhav et al. (2017), who examined the progress and efforts made in adopting solar technologies across member countries. The study provides an overview of solar PV and solar thermal implementation in each SADC country and highlights common regional challenges. It notes that most countries focus more on deploying solar projects rather than developing local industries. The study also points out that financial support, regulatory frameworks, manufacturing capacity, and research institutions are still limited in the region. However, the analysis mainly centers on individual countries rather than offering coordinated regional strategies, which results in a lack of focus on regional integration.

A more recent study by Justo et al. (2022) explores the renewable energy landscape in the SADC region, covering sources such as hydropower, solar, wind, biomass, and geothermal energy. Although the study does not focus on the integration of the solar PV value chain, it highlights the role of regional institutions, particularly the Southern African Power Pool (SAPP), in supporting solar PV deployment and cross-border power system integration. Complementing this, Ndubuisi and Avenyo (2024) emphasizes the need to harness Africa's critical mineral reserves, growing energy demand, and increasing political momentum around industrialization. Their recommendation for a coordinated regional industrial strategy offers valuable insight into how African regions, including SADC, can specialize in different parts of the value chain to build a stronger and more integrated renewable energy sector.

Furthermore, regional trade shows a growing trend in the SADC region, indicating an improvement in market integration effort. According to Black et al. (2020), regional trade within the SADC grew significantly from 2000 to 2016, both in value and as a share of total exports, increasing from 20% to 25%. This growth was supported by strong regional economic growth and the reduction of tariff barriers following the implementation of the free trade agreement from 2000. Intra-SADC import shares also rose, reaching 23% in 2016, indicating increased integration within the regional market. Additionally, Black et al. (2020) suggest that the long-term sustainability of regionalism depends on recognizing the importance of regional industrial policy that accounts for the dynamics of GVCs and RVCs, ensuring benefits are widely distributed, and fostering partnerships between governments, retailers, and local suppliers.

Regional value creation and economic integration are also among SADC's main priorities. To support this, efforts have been made to strengthen collaboration between the SADC Secretariat, member states, and various sectoral bodies. One key initiative is the Support towards Industrialisation and the Productive Sectors (SIPS) program, which ran from September 2019 to May 2024 with funding from the European Union (EU) and the German Federal Ministry for Economic Cooperation and Development (BMZ). The program aimed to address coordination and market gaps between national and regional levels, as well as between the public and private sectors. The interventions including the development of three selected RVCs, including Pharmaceutical, Medtech, and Leather products, which unfortunately, solar PV sector was not included in its scope (GIZ, 2024).

Nevertheless, to boost the value-added activities within solar PV value chain, some countries under the SADC region have implemented national strategies by collaborating with other countries outside the continent. Usman and Csanadi (2023) mentioned that on December 2022, the US and the DRC and Zambia signed an MoU to strengthen the supply chain of electric vehicle batteries. The DRC is the world's largest producer of cobalt and Zambia is a major producer of copper, where both are also the key minerals used in solar panels production. Black et al. (2020) strengthen the point where SADC countries are generally positioned more upstream in GVCs, with a high share of their value-added exports embodied as intermediate inputs in other countries' exports (forward linkage). This reflects the resource-intensive nature of the region's exports. Furthermore, Shopia. et al. (2024) named South Africa as a highest performers for Chinese PV investment due to the fact that it has a strong manufacturing sector of the economy, provide a strong regulatory framework for investment in renewable energy resources and also has a strong solar PV potential. The government is committed to enhance the industrialization of the PV value chain by publishing the South African Renewable Energy Masterplan (SAREM).

In short, to fully-capitalize the resources available in the countries, Africa must integrate its mining sector into the broader economy, foster regional cooperation, and invest in infrastructure and human capital, aligning with the Africa Mining Vision. Manufacturing solar PV is mineral-intensive and the rapid growth of solar PV manufacturing for instance, is enhancing local capabilities with new markets and jobs, driving increases in infrastructure investment, providing opportunities for industrial development, as well as contribute to sustainable energy (Malima et al., 2024; Ndubuisi & Avenyo, 2024).

3
Theoretical Framework

This chapter outlines the established theories used to guide the methodology and operationalization of the research, to ensure that data collection and analysis are coherent with the theoretical lens. The framework adds to the understanding of regional integration and the solar PV value chain by providing guidance to explore the challenges of aligning national priorities with the goals of regional and international institutions.

3.1. Multilayer Analytical Framework: a Pathway towards Regionalizing PV Value Chain

The term of regionalizing PV value chain resonates with the concept of Regional Value Chain (Pasquali et al., 2021), Regional Economic Integration and Regional Integration (Bala, 2017). The idea of regionalizing solar PV value chain is meant to consolidate the scattered mineral resources, underutilized production capacities, and limited investments in each country under the SADC region. Align with Goodrich et al. (2013), that have said that *"innovation may be accelerated by combining asymmetric regional strengths"*. Practice has shown that when countries make use of each other's strengths and support each other's weaknesses, it creates opportunities for them to specialize, grow larger production capacities, and lower production costs (Bala, 2017). Thus it is important for regions (countries under common regulatory regimes or preferential trading rules for the regional members (Pasquali et al., 2021)) to pursue collaborations that leverage one another's asymmetric strengths for mutual benefit.

Ndubuisi and Avenyo (2024) argue that regionalizing solar PV industry is a complex approach due to the geopolitical interest at play. Regional integration introduces uneven exposure to risks (e.g. infrastructure costs, FDI attraction, regulatory compliance), which makes joint commitments difficult without mechanisms to balance incentives. Some other challenges to reach a greater progress in regional integration including the inefficiency of regional bodies that distribute the cost and advantage of integration between country members, difficulties of an economic nature such as obstacle to intensifying trade and monetary problems, and those of a political nature such as the weakness and even the lack of political will of member states (Bala, 2017).

Different forms of governance (e.g. global, local, social, public and private actors) do not operate in isolation, they interact at the same time, shaping how regional value chains are structured. The institutions behind those governance forms can either harmonize or be conflicting and thus can facilitate or hinder the evolution of a regional value chain (Hulke & Diez, 2022). However, research on the role of public and private governance interaction to inform strategies in regional value chains in the global south remains limited (Krishnan, 2018; Pickles et al., 2015) in (Pasquali et al., 2021). While, Pasquali et al. (2021) studying the interaction between public and private governance (trade, investment, and labour policy regimes) from national, regional and global levels of analysis, the understanding of the dynamics of regional value chains remains limited. Other than institutions interaction dynamics, knowledge and information flow, technological capabilities, policies and market creation are also considered as important factors in in the development of emerging technology sectors (Hekkert et al., 2011; Hekkert et al., 2007; Huang et al., 2016). Therefore, this research offers an approach that combine both institutional and socio-technical aspects as factors that determine the dynamics of regionalizing solar PV value chain, making the propose **multilayer analytical framework** (see Figure 3.1) as a suitable approach to operationalize the strategic interventions in regionalizing solar PV value chain in the SADC region.

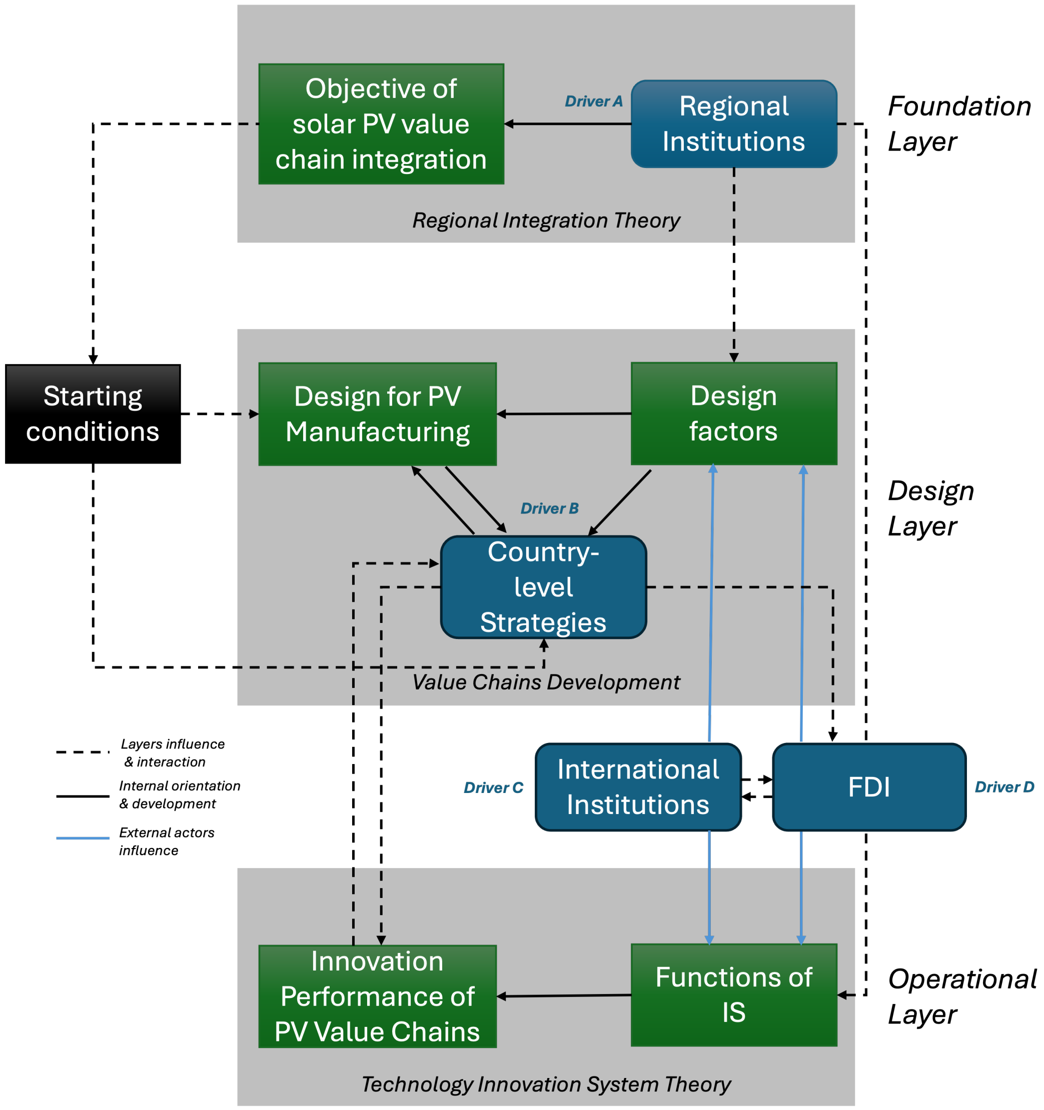

Figure 3.1: A Multilayer Analytical Framework
Source: Author's own compilation

The framework is building on the approach from Elabbas et al. (2023) who originally applied it to organize various elements in the institutional context to analyze the dynamics integration of African power pools. While the overall structure of the framework is retained, this research introduces several key theoretical modifications that represent an original contribution to the study of regional solar PV value chain integration. These modifications reflect the distinct technological transition, design for manufacturing, and institutional characteristics of the solar PV sector and aim to uncover context-specific barriers, driving forces, and strategic interventions.

Ultimately, this research **contributes to the creation of theoretical framework** for designing a regional integration in solar PV value chain by focusing on the socio-technical aspects and the institutional interventions. The innovative contribution of this framework lies in the substitutions of organizational factors with system functions from the innovation systems literature, the adoption of design constraints tailored to solar PV manufacturing, and the application of regional integration theory. The concept of innovation system, particularly *technology innovation system* (TIS) shows how actors in every segment of solar PV value chain interacts and operates the flow of technology and information to turn idea into a successful process and product in the market at the SADC region. Assessment criteria from Macé et al. (2023) is utilized to evaluate solar *PV manufacturing suitability* and what factors need to be improved in order to develop solar PV manufacturing in a country or region. The design criteria substitutes the design factors that constraint the design process of power pool from Elabbas et al. (2023). *Regional integration* theory is also applied in this research to describe how regional organizations can be established and developed to push the objective of solar PV value chain integration. Finally, the term of *"driving forces"* is used to define institutions that drive changes within the regionalizing efforts.

3.2. Technology Innovation System

Hekkert et al. (2007) explains the innovation system as all institutions and economic structures that affect both rate and direction of technological change in society. The TIS concept goes beyond just the technology itself, but includes all the elements that influence how that technology is developed, adopted, and improved throughout the innovation process (Bergek et al., 2008). To understand the determinants of change, it is essential to map the activities occurring within the system, as change results from multiple interrelated activities. However, due to the complexity and diversity of activities in TIS, mapping all of them is impractical. Therefore, only relevant activities should be considered. In the literature, activities that contribute to the goals of an innovation system, whether positively or negatively, are referred to as "functions of innovation systems". Table 3.1 shows the seven functions that will be utilized in this research.

Table 3.1: Functions of Innovation System

Function	Description
F1 - Entrepreneurial activities	Entrepreneurs play a crucial role in ensuring an effective innovation system by transforming new knowledge, networks, and markets into tangible actions that create and capitalize on business opportunities.
F2 - Knowledge development	Mechanisms of learning are at the heart of any innovation process. R&D and knowledge development are prerequisites within the innovation system. This function encompasses 'learning by searching' and 'learning by doing'.
F3 - Knowledge diffusion through networks	The essential function of networks is the exchange of information. Network activity can be regarded as a precondition to "learning by interacting". This function can be analyzed by mapping the number of workshops and conferences devoted to a specific technology topic and by mappiing the network size and intensity over time.
F4 - Guidance of the search	Given the limitations of resources, it is essential to prioritize specific technological options for investment when multiple alternatives exist. Without such selection, resources may be spread too thin, reducing the effectiveness of each option.
F5 - Market formation	New technologies often struggle to compete with established ones, making protected spaces essential for their development. This can be achieved through temporary niche markets, allowing actors to learn and shape expectations, or by providing a competitive edge through favorable tax policies or minimum consumption quotas.
F6 - Resource mobilization	Both financial and human resources are fundamental to all activities within the innovation system. This includes funding for long-term R&D programs initiated by industry or government to advance technological knowledge, as well as financial support for testing new technologies in niche experiments.
F7 - Creation of legitimacy	For a new technology to succeed, it must either integrate into the existing system or disrupt and replace it. However, stakeholders with vested interests often resist this process of disruptive change. In such situations, advocacy coalitions can play a crucial role by acting as catalysts; they help bring attention to the new technology, lobby for resources, and push for favorable tax policies, thereby building legitimacy for the emerging technological path.

Source: Hekkert et al. (2007)

It is essential to carefully define the system boundaries prior to conducting TIS analysis (Markard et al., 2015). This research delineates its analysis by incorporating the vertical dimension (related to technology value chains), as conceptualized by Bergek et al. (2015). We will extend the TIS analysis to the entire value chains to analyze the level of system performance in each segment of the value chains (upstream, midstream, and downstream, as explained in the chapter 2). It implies that all the actors, networks and institutions that contribute to every segment of solar PV value chain must be included, yet limited by spatial aspects (Chinese case and the SADC's case).

Some studies emphasize that the set-up of value chains is an important part of the system building process to ensure the efficient flow of resources, knowledge, and technology across different segments, enabling innovation, market formation, and long-term industry growth while addressing bottlenecks and integration challenges. Welie et al. (2019) provides an example of how to assess the performance of TIS in every segment of the value chain. Using the heat-map table, the paper visualizes where functions or segments are advanced or lagging.

Table 3.2: Indicators per System Function

Function	Indicator
F1 - Entrepreneurial activities	Organization or companies entering/leavng the market
	Size of companies
	Export activities
F2 - Knowledge development	Research and technological project
	Demonstration and pilot projects
	Learning by doing and learning by using
	Patent
	R&D investment/expenditure (both from private and public)
F3 - Knowledge exchange	National knowledge exchange between organizations (e.g. via workshops, conferences, joint projects)
	International knowledge exchange (e.g. in joint research projects, international cnferences or seminars)
F4 - Guidance of the search	Targets set by the government of industry
	Expectations and opinion of experts (positive/negative)
	Regulations & policies
F5 - Market formation	Financial market incentives (e.g. stimulation programmes)
	Tax regimes
	Market size
	Project installed
	Import share
F6 - Resource mobilization	Financial resources (e.g. subsidies fo and investments in the technologies in the technology)
	Human resources (skilled labour)
	Physical resources (infrastructure, material etc)
F7 - Creation of legitimacy	Extent to which the technology is promoted by organizations, government (adwads, brochures, competitions)
	Lobby activities for/against the technology

Source: Bergek et al. (2008), Hekkert et al. (2011), Mensah et al. (2024), and Vasseur et al. (2013)

To apply the TIS framework, this research uses specific indicators linked to each system function (see Table 3.2). Following the guidance of Markard et al. (2015), both internal (endogenous) and external (exogenous) structural elements that influence system dynamics are taken into account. Previous studies, such as Vasseur et al. (2013), have classified factors like import share, export activity, international knowledge exchange, and FDI as international influences on PV innovation systems. Similarly, Lall and Pietrobeli (2005) and Mensah et al. (2024) include capital goods imports, FDI, and licensing as elements that shape a country's technological capabilities. However, this study takes a different approach. Rather than including international institutions and FDI as standard TIS indicators, they are instead treated as external driving forces that support regional integration efforts. For example, trade activities such as importing and exporting solar components can be shaped internally by regional institutions that promote cross-border cooperation. International institutions, which often provide technical and financial support (Elabbas et al., 2023), are more accurately viewed as enablers of knowledge and technology transfer at the regional level. Likewise, FDI, typically involving multinational corporations that serves as a separate driver of industrial development, not a direct function within the TIS framework. This distinction allows the analysis to better capture the role of these actors in advancing regional solar PV value chain integration, rather than limiting them to indicators within the innovation system itself.

The indicators will be used in structuring the data collection process by systematically track relevant events linked with the indicators. The list varies slightly from previous study by Vasseur et al. (2013), combining with some indicators defined by Bergek et al. (2008), Hekkert et al. (2011), and Mensah et al. (2024). Regulations and policies is being added as one of the indicators under the function of *guidance of search*. Regulations and policies is said as one of the factors that influence the direction of search within the technology innovation system that must be sufficient incentives and/or pressures for the organization (Bergek et al., 2008; Hekkert et al., 2011). Moreover, patent and R&D investment/expenditure is added to the function of *knowledge development*, and project installed to the function of *market formation*. Patent (Hekkert et al., 2011; Mensah et al., 2024) and R&D investment both from private and public sector (Mensah et al., 2024) are some of the technological efforts that drive the ability o acquire technology and adapt to changing market circumstances. Project installed is being added as indicator in market formation, for instance solar power generation planned, site allocation and constructed (Hekkert et al., 2011).

3.3. Design Factors in Solar PV Value Chain

As suggested by Macé et al. (2023), there are four main design factors that determine the design process of solar PV value chain, categorized into baseline requirements, key requirements for CAPEX-intensive steps, key requirements for OPEX-intensive steps, and key requirements for competence-intensive steps. Meaning that to evaluate the potential to develop solar PV manufacturing in a specific region or country, it is crucial to understand the most influential factors, which can be seen in Table 3.3. Every factor encompasses several elements that the level of importance differs in every segment of the value chain which expressed by the scoring from 1 (less important) to 3 (very important) (see Appendix 9).

When there are already companies working in the upstream segment in a region, it shows that developing local manufacturing is possible. This also create a chance for new businesses to become important suppliers or buyers for those existing companies (Macé et al., 2023). The initial stages for the formation of the photovoltaic cells (silica extraction, silicon production, ingot and wafer production), including raw materials processing are known as a segment that require a high and specific technological level and a high investment cost in the facilities (Garlet et al., 2020). Thus, it is a very crucial segment among PV manufacturing activities (ETIP, 2023). Moreover, the successful semiconductor industries paved the way for further PV value chain development (Huang et al., 2016; Su, 2013), showing the presence of existing industrial ecosystem. Each segment of PV value chain requires different ecosystem to establish and scale-up. Upstream industries require capital-intensive nature of raw material extraction and processing, midstream industries require connected logistic networks, skilled labor pools, and proximity to major markets, while downstream sector tends to cluster around urban areas with higher energy consumption and favorable renewable energy aoption (Wang & Liu, 2024). In short, industrial clusters can facilitate the rapid developments of the solar photovoltaic industry and the prompt establishment of a complete industrial value chain (Su, 2013). Moreover, proximity to key resources, integrated logistic infrastructure, skilled labour also mentioned as crucial things to consider.

According to IEA (2022), electricity provides 80% of the total energy used in solar PV manufacturing, where 60% of energy supply generates from coal energy source. The availability of energy supply and low-cost electricity are not the only important things in powering PV manufacturing, low-carbon electricity can also improving its competitiveness, thus both are crucial to be considered in developing PV manufacturing in a region. In regards political and financial uncertainty, research from Goodrich et al. (2013) found that low-cost labour itself isn't the main reason why PV manufacturers put their factories in China. It is because when that factor is combined with inflation and risk of doing business in China, there was no significant price advantage for the industry. Instead, Goodrich et al. (2013) conclude that innovation and supply-chain development have the advantage to reduce cost by 40-50% and increase performace about 50%, potentially making local manufacturing more viable and then shape the factory-location decisions. Therefore, R&D center and IP protection are also important to be considered in choosing the region as PV manufacturing location.

3.4. Regional Integration

In line with Elabbas et al. (2023), a regional integration theory (RIT) defined by Schimmelfennig (2018) is utilized in this research framework. RIT seeks to explain the establishment and development of regional international organizations (RIOs). The SADC as a regional economic community (REC) is considered as RIO because it fulfills the attributes of RIOs, including: *first*, established by states and have states as their members; *second*, REC is organization, which has its organizational structure, headquarter office, and has capacity to make decisions; *third*, it consists of more than two member states (which consists 16 countries member); and *four*, the membership is geographically proximate and limited to the southern part of Africa. Moreover, other organizations in the energy sector, like SAPP is also suitable to be called as a RIO.

The key questions along with the theory based on Schimmelfennig (2018), including:

1. Why states decide to establish and how they design regional integration?
2. Under which conditions and how RIOs expand their tasks, competencies, and members over time?
3. What impact do RIOs have on the states and societies in their regions and how do these impacts condition the future development of RIOs?
4. Why are some countries or issue areas more integrated than others, and why do some stagnate or disintegrate whereas others progress?

In the African context, AfDB (2019) highlight that one of the main goals of regional integration is to support industrialization by creating larger, more unified markets. Strengthening regional ties and aligning with global value chains, through improved technical and labor standards, can help countries move up the industrial ladder and reduce external trade imbalances. Black et al. (2020) further explains that regional integration and the growth of RVCs are closely connected. RVCs help link economies by enabling the free movement of goods, people, and capital across borders. This not only opens access to larger markets and allows firms to scale up, but also encourages learning, skill-building, and specialization within firms. As a result, RVCs contribute to deeper integration by creating backward, forward, and horizontal value linkages between businesses in different countries, driving broader structural transformation.

Furthermore, Black et al. (2020) also points out that regional integration can be accelerated when the private sector actively pushes governments to improve access to regional markets, lower trade barriers, and invest in cross-border infrastructure. This is more likely to happen in regions where RVCs are already well developed, creating strong business incentives. However, governments must also do their part by supporting supplier development and partnering with stakeholders to help local firms join and benefit from regional value chains. For regional integration in Southern Africa to be sustainable in the long run, there must be a clear focus on industrial policies that reflect the realities of both global and regional value chains, promote regional cooperation, and ensure that the benefits are widely shared across countries and communities.

3.5. Driving Forces

To represent the dynamic forces, ”motors of change” concept from transition management literature is also being applied in this research. Hekkert et al. (2007) introduce this concept to describe the dynamic of actors, their relations and institutions within innovation systems. While in this research, we modified the term into ”driving forces” as we want to explain the forces that drive the attempt in regionalizing solar PV value chain amid diverse institutions. Moreover, Beyer (2007) also use the same concept to describe the role of organizations in policy-formation processes, and Hulke and Diez (2022) and Pasquali et al. (2021) who describe the role of private and public institutions in driving the development of regional value chains.

Four driving forces that leverage the regional integration in solar PV value chain are identified through literature study, including regional institutions, country-level strategies, international institutions and FDI.

Regional institutions refer to the regional bilateral or multilateral organizations such as European Union (EU), which is a subset of international institutions that offers exclusive benefits like trade advantage, development funding or political influence to the country members. These benefits attract the attention of non-member non-state actors like firms, NGOs, or civil society organizations (Anghel & Jones, 2025).

In African context, regional body or REC, influences the higher-level objectives and foundation as well as the operationalization of the development agenda (Elabbas et al., 2023). REC can influence the higher-level objectives and foundation of solar PV integration (e.g. regional targets, integration strategies, policy harmonization), as well as the operation level through funding, coordination, and capacity building, acting as one of the actors in the solar PV innovation system. It also has the means to impact the design factors to facilitate the development of solar PV manufacturing (for instance, by promoting cross-border industrial partnerships and mobilizing funding for transnational infrastructure).

Moreover, country-level strategies which a nation's coordinated policy framework and actions, is designed to develop, scale and sustain the local solar PV industries (e.g. prioritizing energy infrastructure to push the development of solar cells manufacturing). On the other hand, once manufacturing begin, its technical and economic characteristics influence how the country updates or adapts its strategy. Hekkert et al. (2007) describes this concept as national intervention that influence the technological progress, price, and diffusion. The researchers provide an example of the development and diffusion of solar cells where it depends on technological progress made in research institutes and universities all over the world. In turn, global diffusion depends on different national policy regimes that stimulate the technology adoption. While, suppliers, manufacturers and installers are the key actors that respond to, shape, and operationalize the country-level strategies.

And finally, the international institutions and FDI act as exogenous factors that influence the value chains development at design layer and the solar PV innovation performance at operational layer. International institutions refer to formal and informal global governance bodies such as World Bank and United Nations that influence rules, norms, and funding mechanisms across bodies. International institutions and FDI influence each other as international institutions play a catalytic role in attracting and shaping FDI by creating a favorable and low-risk environment (for instance, by providing policy and regulatory framework for countries to facilitate and attract FDI (UNESCAP, 2017)), while FDI can reshape institutional strategies making them more responsive to market opportunities and private sector needs. Meanwhile, countries also need to facilitate the investment environment to attract quality FDI, thus knowledge and technology import can be optimum. As Rao et al. (2024) mentioned that a positive relationship between FDI and innovation depend on the ability to absorb knowledge and quality of governance in the recipient countries.

Table 3.3: Design Factors for Solar PV Manufacturing Development

Factor	Indicator
Baseline requirements	Fundamental conditions that determine whether a location is suitable for any manufacturing step.
Existing industrial ecosystem	A developed industrial base in the region or country supports further growth and manufacturing expansion.
Existing of upstream PV actors	Existing local PV manufacturers enhance supply chain opportunities and partnerships.
Infrastructure readiness	Reliable electricity, water, and transport networks enable efficient operations and logistics.
Availability of raw material	Proximity to key resources lowers costs and improves supply security.
Domestic solar demand	A strong local market ensures consistent demand and reduces transportation and logistic costs.
Ease of doing business	A broad indicator defined by World Bank, which includes a series of element such as favorable regulations, streamlined permits, and legal stability that can attract investment and manufacturing.
Key requirements for CAPEX-intensive steps	Key factors needed for capital-intensive steps such as polysilicon and wafer production.
Access to capital	An access to capital depends on project-specific factors (e.g., revenue security, risk level) and the availability of financial institutions in the region or country.
Interest rates	Key influence factor to influence competitiveness and are determined by similar factors, including risk level and economic or political conditions.
Key requirements for OPEX-intensive steps	Factors affecting ongoing operational costs.
Electricity cost & supply	Affordable and reliable electricity is essential for reducing operational costs.
Carbon intensity	Low-carbon electricity sources (e.g., hydropower, renewables) are crucial for meeting environmental standards and regulations.
Labor costs	Despite automation, certain PV manufacturing processes remain labor-intensive, making the cost of low-to-medium skilled workers an important factor.
Key requirements for competence-intensive steps	Requirements for high-technology or innovation-driven steps.
Availability of qualified labor	Some PV manufacturing steps require skilled labor, which can be addressed through training programs, though highly specialized roles remain harder to fill.
R&D centers	Essential for staying updated with technological advancements, optimizing manufacturing processes, and enhancing efficiency.
IP availability	Access to patented technologies, whether owned or licensed, can be advantageous but is not mandatory for success.

Source: Macé et al. (2023)

4 Methodology

4.1. Research Design

This research is grounded in a socio-technical approach, as it examines the interplay between technological development, economic structures, and governance factors. A qualitative case study approach is conducted to deeply explore the institutional interventions and the socio-technical factors that hinder and support in the development of PV value chain. The development of the solar PV sector in China and the SADC region will serve as case studies for this research. SADC is selected for this study because several of its countries can play key roles in the solar PV value chain. For instance, DRC and Zambia as major producer of copper and tin, and South Africa with its strong regulatory framework on renewable energy investment.

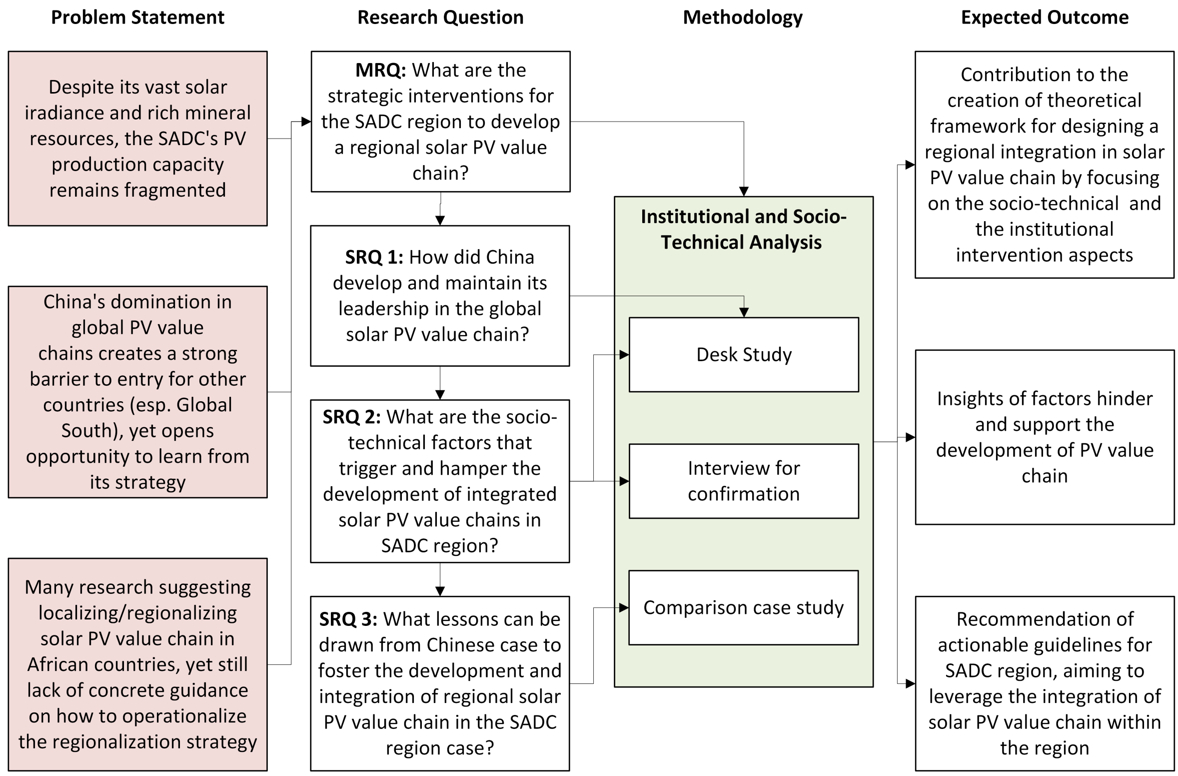

Figure 4.1: Problem Statement, Research Questions, Methodology and Expected Outcome Visualization
Source: Author's own compilation

The flow of how this research is designed can be seen in Figure 4.1. It depicts the study design, linking the problem statement, with the research question and methodology, to get the expected outcome of this research.

4.2. Research Method

Figure 4.2 depicts the research flow that was established to answer the research questions. The research began with preliminary literature review to get the firm ideas of the empirical problems and to help the researchers to formulate the research objectives and research questions. Later, a more in-depth literature review was conducted to elaborate on the current global PV value chains situation and to structure the theoretical framework for this research. Finally research methodology were developed, including how the data collections and analysis will be proceed to reach conclusion. Further explanation on the data collection and analysis will be explored in the next section.

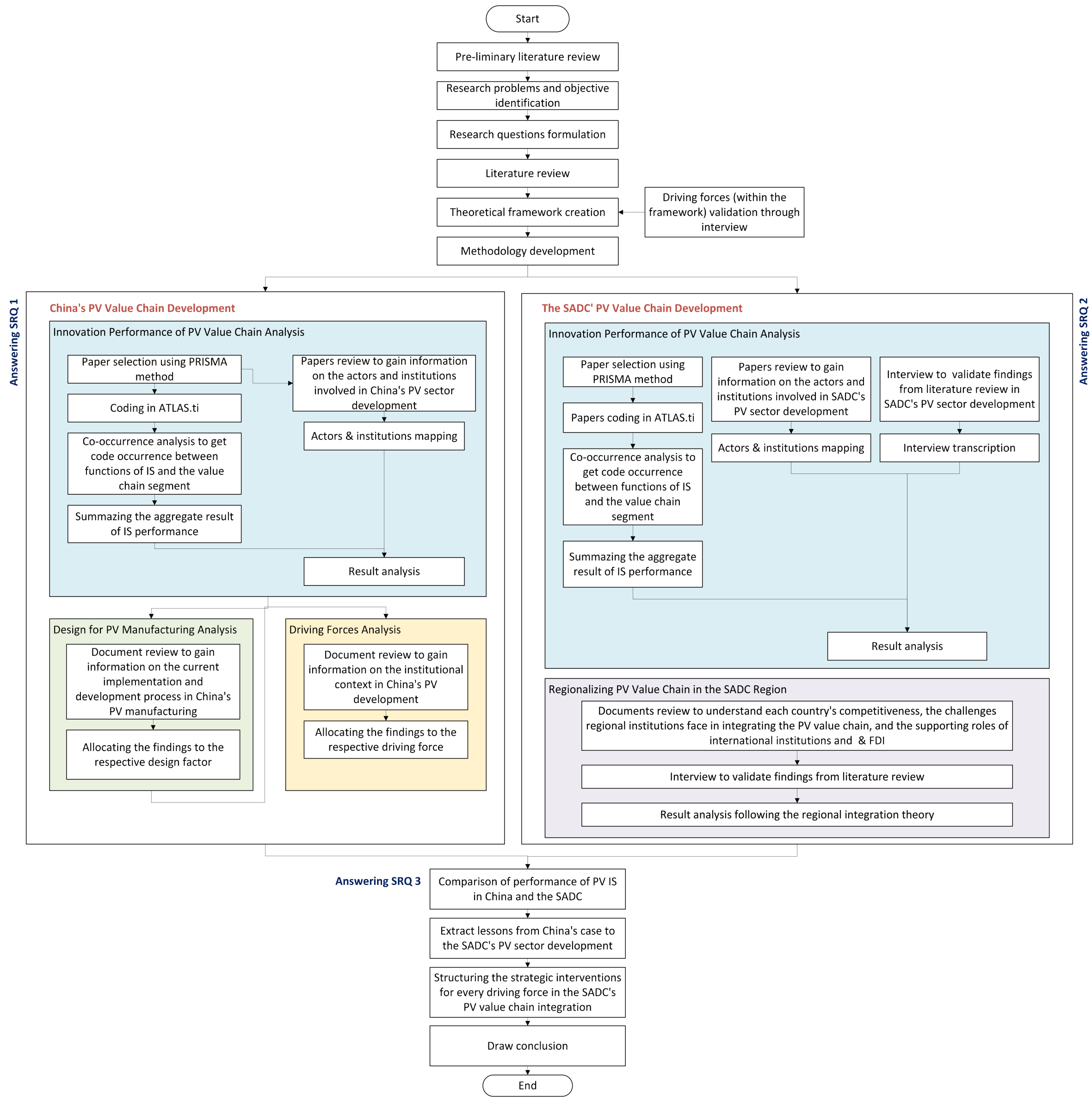

Figure 4.2: Research Flow
Source: Author's own compilation

Moreover, this research assesses and compares the innovation performance of solar PV value chains between Chinese case and the SADC region's case. It further analyzes how China designing the ecosystem for its PV manufacturing development and how the institutions drive the development of its PV sector. In other side, the study explores the role of regional institutions, international institutions and FDI in integrating solar PV value chain in the SADC. By comparing these two cases, the research aims to extract lessons learned and strategic insights to inform and guide the integration of solar PV value chains in the SADC context.

4.3. Data Collection

This study mainly employs literature study as data collection approach, with interview for findings confirmation, utilizing both primary and secondary data to gain a comprehensive understanding of the institutional and socio-technical dynamics in shaping the development of PV value chain. A slightly adapted methodological approach is applied to each case study to draw context-specific conclusions.

4.3.1. Desk Study

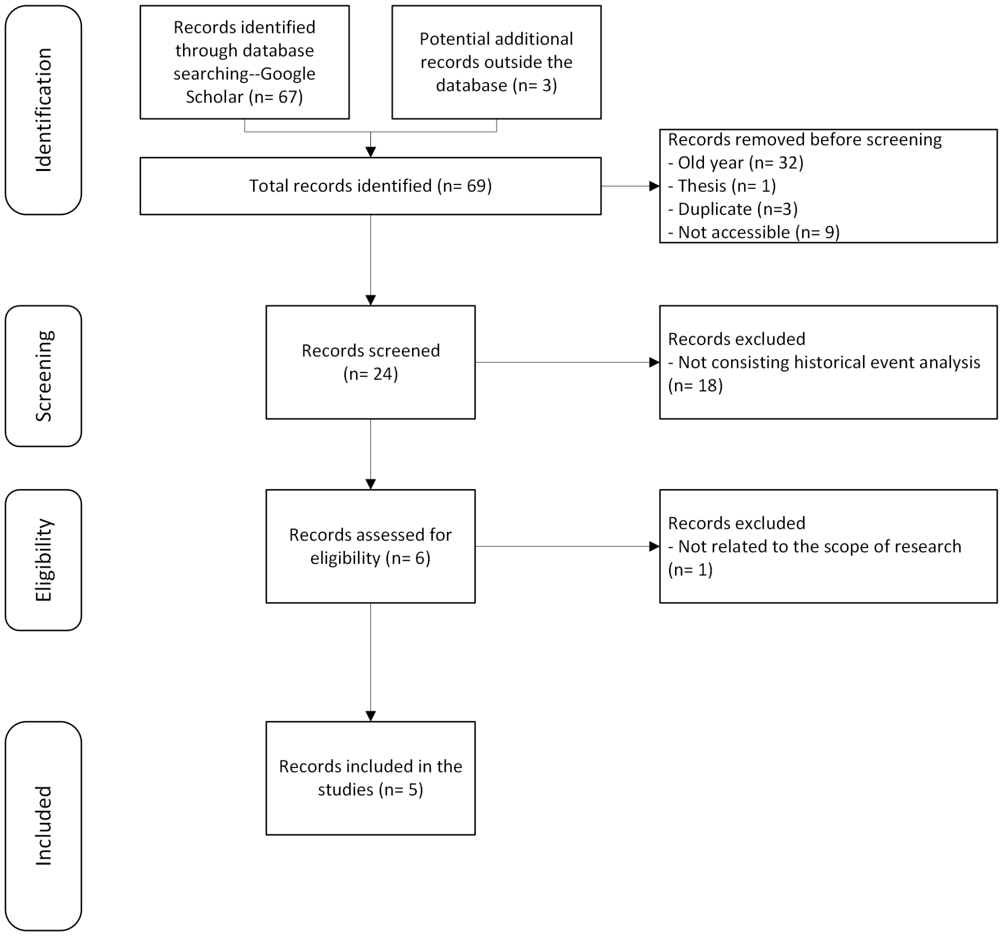

Figure 4.3: Paper Selection for China's IS Performance Assessment
Source: Author's own compilation

For the case of China, the research will rely entirely on secondary data collected through a desk study. This study aims to examine the historical trajectory of PV development in China to assess the IS performance, investigate both the hard and soft infrastructures that have influenced the growth of the PV manufacturing sector, as well as the institutional drivers behind its development. To assess the performance of the innovation system, five empirical studies analyzing historical events in PV development will be used as the primary sources for the coding process. These studies will be selected using the PRISMA method (see Figure 4.3).

The study begins by searching the relevant literature on Google Scholar using the keywords "solar photovoltaics" OR "PV", "Industry Development" OR "Innovation System" OR "Transition" OR "Policy", and "China", with advance setting only for showing articles with title following the keywords (allintitle). It's resulted 67 articles, then three articles were added outside of the database. Before the screening, several records were then removed due to old records (published before 2014), thesis paper, duplicate, and because the articles cannot be accessed. The records were screened by reviewing their titles, followed by checking the results or analysis sections to determine whether they included a historical analysis. Articles that do not contain such analysis were excluded. Finally, the remaining articles were assessed for eligibility. One article was excluded at this stage because it focused on a comparison between China and Germany, rather than on China's policy development.

PRISMA approach was also being applied to identify the five papers used for coding in the assessment of TIS in the SADC region's PV development case. There was a slightly difference process due to limited publications that explore the solar PV development event in the SADC countries, compare to the studies in China's PV development. Figure 4.4 depicts the process involved in the articles selection.

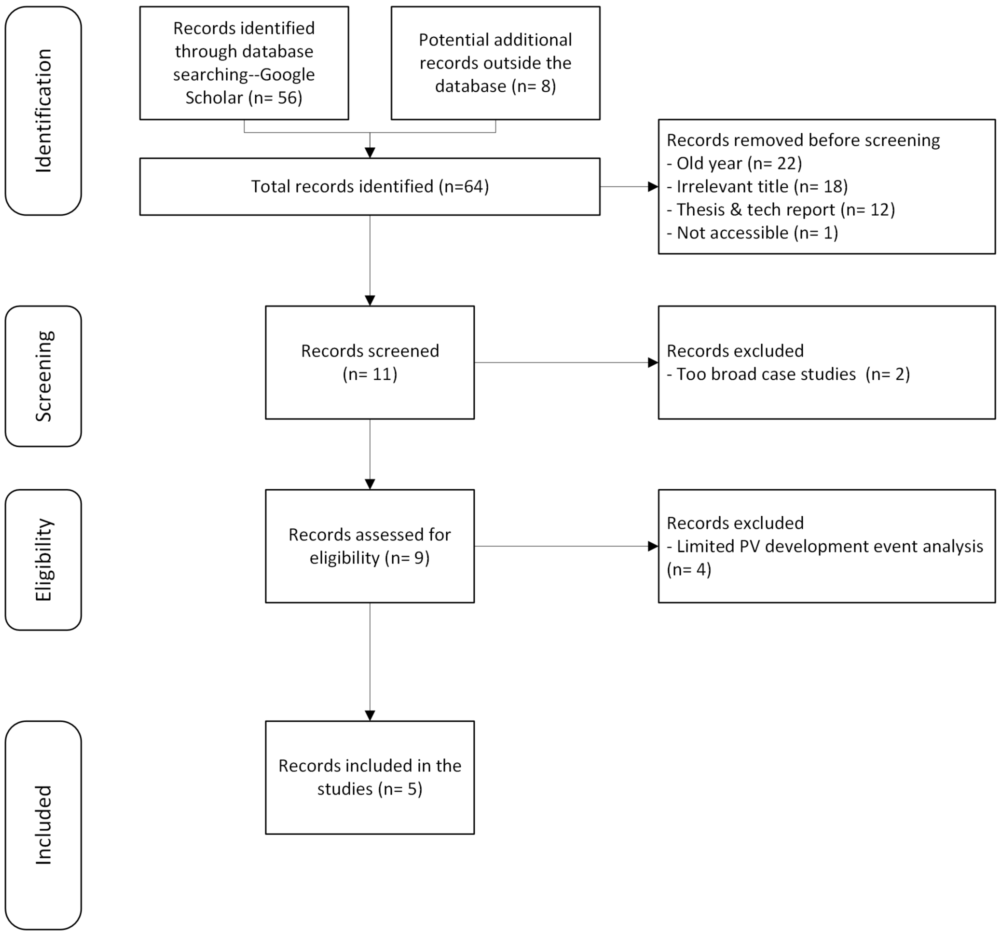

Figure 4.4: Paper Selection for SADC's IS Performance Assessment
Source: Author's own compilation

The same primary peer-review website (Google Scholar) was utilized to find the papers using these keywords: solar photovoltaics" OR "PV", "Industry Development" OR "Innovation System" OR "Transition" OR "Policy", "Southern Africa". The utilization of *allintitle* feature in the advance setting causing no appearance of papers in the database, therefore this feature cannot be utilized. Furthermore, it causes the appearance of papers with irrelevance title, affecting the total records for the screening step is only 11. Because of the limited available publications, papers that passes the eligibility step are the ones that analyze the PV development process in either Southern Africa (the SADC region) as in the regional (multi-country) perspective or papers focusing on only one SADC country. Finally, five papers consisting the development events of solar PV development were chosen.

Furthermore, desk study both from grey literature, peer-reviewed articles also statistical and data source were employed to support the result from the IS assessment, and to explore other information to do the rest of the analysis step. This data collection approach will be used to generate results among these steps of analysis:

1. China's case: Elaborating the result from TIS performance assessment
2. China's case: Fulfilling the design criteria in PV manufacturing development

3. China's case: Fulfilling the driving forces roles in PV development
4. SADC's case: Elaborating the result from TIS performance assessment
5. SADC's case: Fulfilling the competitiveness factors for each country member and identifying the challenges and role of regional institutions and other institutions in designing the regional solar PV value chain
6. Elaborating the recommendations for the strategic interventions in integrating solar PV value chain, from every driving force

4.3.2. Interview

Primary data was collected through interview to validate the findings from desk research, particularly for the SADC region perspective. The interviews target representatives from at least one of the key driving forces within the SADC region context, such as individuals from the REC offices, international organizations, national government agencies, and/ or representative from multinational or local companies operating in the region. Respondents will be contacted via LinkedIn and email, with outreach limited to the researcher's existing professional network. This constraint may introduce sampling bias, as some crucial stakeholders involved in PV development might be excluded simply because they are not within the researcher's immediate reach. To mitigate this limitation, a literature review will be conducted to supplement and support the analysis.

Table 4.1 is the list of interview respondents of this study, along with the codes that are used to identify them in the following chapters. Foreign government body reflects public organization in other country that actively collaborating with SADC to improve renewable energy sector, particularly solar PV. The interview aims to gain validations from the international institutions perspective in seeing the solar PV development effort in the region.

Table 4.1: Interviewees List

Stakeholder Group	Interviewee	Code
International institution	Circular Economy & Renewable Energy Sector Expert in Foreign government body	A1

Interviews conducted in a semi-structured format using online video conferencing platforms. Recording will only take place with the explicit consent of the interviewee. In cases where recording is not permitted, detailed transcription will be carried out to ensure accurate documentation of the information collected. The interviews structured around three phase: (1) General questions; (2) Validation questions; and (3) Exploration questions. The general questions are meant to ask about the interviewee expertise and to ask if there are anything to be confirmed before the interview starts. Validation questions are meant to validate the findings drived from desk study, while exploration questions are to ask the possible recommendations from the experts. This structure will be formalized in an interview protocol (see Appendix 9) to ensure consistency across interviews and to support systematic data collection.

4.4. Validity and Reliability

This section outlines the strategies used to ensure the validity and reliability of this qualitative study, with the aim of preserving the accuracy and consistency of the research findings. As noted by Sekaran and Bougie (2016), validity can be divided into internal validity, referring to the accuracy of data collection, and external validity, which concerns the extent to which findings can be generalized to different contexts. Reliability, on the other hand, involves the consistency of data interpretation and the stability of coding schemes when applied by different researchers.

To strengthen the validity of the study, triangulation is employed. This involves collecting data from from desk study, combines with validation from interview. These sources are then analyzed in relation to one another to assess consistency, highlight common themes, and ensure that the conclusions are supported by a convergence of evidence (Baxter & Jack, 2008). During the interview phase, a pragmatic and iterative approach is adopted, where interview questions are continually refined in response to emerging insights from preliminary data. This flexible process allows the research to adapt to evolving themes and ensures alignment between data collection and the study's focus. It also contributes to reliability, by making the questions more responsive and inclusive of relevant topics.

Additionally, peer debriefing sessions are conducted with supervisors to review and reflect on the research process, data interpretation, and emerging conclusions. These sessions provide critical external input, helping to identify potential sources of bias and reinforcing the reliability of the findings through collaborative scrutiny. To promote transparency and support the generalizability of the research, detailed documentation is maintained for all aspects of the study, including methods of data collection, transcription protocols, coding procedures, analytical decisions, and any modifications made to the research design.

4.5. Data Analysis

In order to answer the research questions, data analysis will be separated into three part, along with the sub-analysis and the step by step.

Part 1: China's PV Value Chain Development
This part aims to answer the first sub-research question. To answer this question, three steps of analysis will be utilized, allowing a comprehensive approach of seeing China's strategy in maintaining the domination in global PV value chain.

- Step 1: Assessing the performance of solar PV TIS. The analysis process involves coding process in ATLAS.ti.
- Step 2: Analyzing the design process to fulfill the criteria in developing PV manufacturing sector.
- Step 3: Analyzing the driving forces on PV sector development. This evolves around the role of institutions in developing solar PV value chain.

Part 2: The SADC's PV Value Chain Development
This part aims to answer the second sub-research question. The socio-technical factors that trigger and hamper the development of PV value chain in the region will be answered using TIS theory and regional integration theory.

- Step 1: Assessing the performance of solar PV TIS, where ATLAS.ti will be utilized as well.
- Step 2: Understanding the competitiveness factors in every country member, as well as the role and challenges of every regional institutions and supporting role of institutional institutions & FDI in designing regional PV value chain.

Part 3: Comparison Analysis
This comparison will be done between the TIS performance in China and SADC. In the end, the result from this comparison, added with the insights from *Step 2* and *Step 3* in **Part 1**, will generate a lesson learned from China's case. Thus, it aims to answer the sub-research question number three.

Part 4: Offering Strategic Interventions Recommendation
Finally, the discussion in **Part 1-3** are integrated to formulate the strategic intervention for every driver in the SADC region.

4.5.1. Coding

Before coding process started, all data including papers and transcripts are ready and can be put in the ATLAS.ti. Documents are stored in the respective folder, each for China's case and the SADC's case analysis.

The coding process plays a crucial role in creating a clear link between the raw data and the resulting findings, discussions, and conclusions (MacQueen et al., 1998). In this study, coding facilitates a more structured analysis by revealing patterns and connections, especially when evaluating the performance of the TIS. A balanced coding strategy was adopted, allowing flexibility to revise or add codes if noteworthy insights emerged during data collection. Initially, a set of predefined codes was developed based on a literature review, focusing on the seven functions of innovation systems and the three segments of the PV value chain.

The coding process began by breaking the data into meaningful segments, such as phrases, sentences, or paragraphs, and assigning annotations and codes to each highlighted part. After generating the initial codes, they were reviewed and reorganized to remove any overlaps or repetition, with similar codes merged together. These refined codes were then grouped under broader categories. For example, codes like ”solar cell manufacturing,” ”PV machinery industries,” and ”module manufacturing” were all placed under the ”midstream” category. These categories were further organized into a few overarching themes that reflect key patterns in the data, aligned with the intended outcomes of this analysis step. This process resulted in a structured and concise set of codes that captures all major topics in the dataset. A full list of categorized codes (the codebook) is available in Appendix 9.

The coding and analysis of interview data were conducted by a single researcher, using predefined criteria and definitions to maintain consistency. However, this approach may limit the validity and reliability of the findings, as the absence of formal inter-coder reliability checks means that the development of codes and themes was based solely on individual interpretation. This introduces the possibility of subjectivity, and different researchers might have drawn different conclusions from the same data. To mitigate this, ongoing self-reflection and critical evaluation were applied to ensure alignment with the research objectives. Nevertheless, the lack of multiple coders for cross-validation remains a significant limitation, highlighting the risk of bias and the benefits of a more collaborative coding process.

4.5.2. Co-occurrence Analysis

As the information are marked with codes, some quotations and codes might have various spatial relations to other quotations. They can overlap each other, one can occupy a part of a larger one, one can also follow the other. To explore how different codes appear together or relate to each other within the data, a co-occurrence analysis is used. This is a feature in the software ATLAS.ti, which helps identify and visualize how often two codes appear in the same or nearby parts of the text, indicating a potential relationship between those concepts.

The concept of co-occurrence construct the coding process in this research, suggesting us to put at least two codes reflecting the categories from innovation system function and the value chain segment in order to see the relation between those codes. Visual aid like table will be used to illustrate these relationships. In this research, the rows show the functions of innovation system and the columns are the segment of value chains. Net value from every function is generated though a deduction from the co-occurrence of positive activities with its negative activities, using Excel function.

4.5.3. Data Normalization

The net values for TIS assessment come from different sources, which every source sits on different scales. For instance, one paper resulted in 219 codes, while another one only has 31 codes (see Appendix 9. If we plotted those numbers as-is, segments tied to the rich source would show up with darker colours in the heat-map simply because it contains more observations, not because it is more important. Therefore, data normalization is needed in this research to rescale the net values into 0-to-1 scales, so we can compare the result between two cases and can see the overall performances of TIS in every case study.

To remove this “text-length bias”, we normalize the data where each net score is rescaled to a common 0–1 range. This research applies min-max scaling normalization, which adjusts data values to a specific range while maintaining the relative differences between them (Kim et al., 2025).

$$x' = \left(\frac{x - \text{oldMin}}{\text{oldMax} - \text{oldMin}}\right) \times (\text{newMax} - \text{newMin}) + \text{newMin} \tag{4.1}$$

Equation 4.1 shows the equation used to calculate a normalized value. A normalized data point, denoted as *x’*, is derived from the original data point *x*. This method relies on the minimum and maximum values of the same attribute in the dataset. Through this normalization process, the original values are scaled to fit within a range of [0, 1] (Ali, 2022).

Here, *x’* represents the normalized value, while *x* is the original data point. *oldMin* and *oldMax* refer to the minimum and maximum values of the original dataset for a given attribute. *newMin* and *newMax* indicate the desired minimum and maximum values for the normalized data.

Finally, the result of data normalization is visualized into heat-map table. After normalization every cell in the heat-map table reflects a function's relative strength, independent of how many sentences we coded. This makes the two case studies directly comparable and allows a fair assessment of overall TIS performance in each segment. By reading the table horizontally we can see how each function performing in all three segments, while reading vertically can see the performances of the TIS in every segment of value chain.

4.5.4. Reporting and Visualization

The main results are presented in a descriptive narrative, accompanied by visual representations that illustrate the performance of factors identified in the analysis. This approach enhances the clarity of complex data and aids in conveying the significance and implications of the findings more effectively.

5 China's PV Value Chains Development

This chapter is organized into three analytical stages, each detailed in the sections that follow. First, we assess the performance of the PV TIS. Next, we evaluate the design process supports PV manufacturing development. Finally, we examine the driving forces behind China's PV-sector growth. The chapter closes by answering Sub-Research Question 1.

5.1. TIS Assessment

The analysis uses 5 research papers that are chosen based on the PRISMA method, using the defined keywords in Google Scholar (see Figure 4.3). Moreover, Table 5.1 depicts the papers included in the coding process, the ones that explored the historical events of solar PV development in China published from 2010 to 2025.

Table 5.1: Research Paper Analysis

Citation	Topic	Description
S. Zhang et al. (2014)	Socio-technical regime in identifying the factors of low-carbon transition in China	Examines the four stages of solar PV policy in China from mid-1990s to 2013. From "the renewable energy-based rural electrification" period, "export-oriented growth" stage, "continued industry support plus market support" stage, to "strong support for distributed solar PV power (DPV) and resource-based categorized FIT" in 2012 onwards.
Huang et al. (2016)	Innovation system analysis on China's solar PV development strategy	Empirically study the rise of the Chinese PV innovation system from 1958 to 2012. This paper divided the historical events into 5 stages of development, including "the beginning era", "opening up of the economy and start of privately-owned entrepreneurial activities", "boost of the PV manufacturing sector triggered by EU market, and "the beginning of the formation of a domestic market for PV".
Y. Zhang et al. (2021)	Changes in government policy and the effects to the solar PV sector	Examine five stages in China's solar PV policy namely from mid-1990s to 2003, from 2004 to 2008, from 2009 to 2011, from 2012 to June 2018, and June 2018 onwards. The first three stages have the same events identification as described by S. Zhang et al. (2014), while two other events including "the rapid development of solar PV in China" in fourth stage and "solar PV after subsidy era" in the fifth stage.
Guilhot (2022)	China's energy policy evolution in transitioning toward a diversivied and low-carbon energy system	Look back at the four decade of China's energy policy, where solar PV sector partly being affected by the regulations. The analysis started from 1981 to 2020 taking the five-year plan policies as the base of analysis, marking the sixth to thirteenth Five-Year Plans.
Bai et al. (2024)	Policy trajectory within China's dynamic PV sector	Employe a bibliometric analysis and content analysis to delve into China's PV polocies over the last two decades, from 2000 to 2022. The evolution grouped into three stages, which are "initial development and domestic demand formation" from 2000 to 2010, "rapid development driven by domestic demand" from 2011 to 2015, and "deepening reform and development" from 2016 to 2020.

Source: Author's own compilation

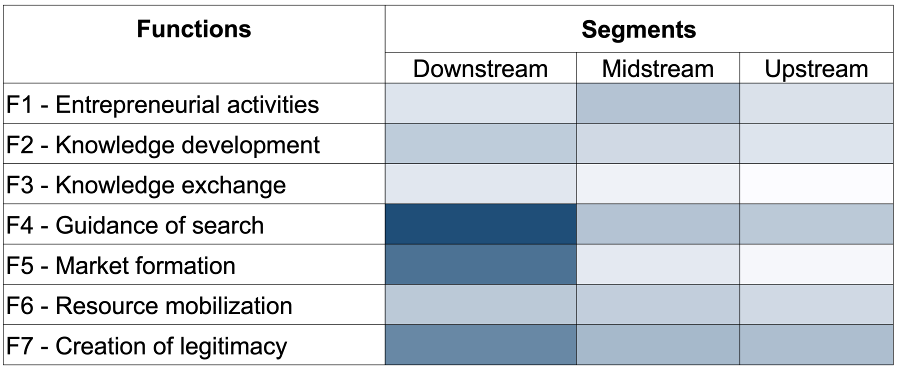

Figure 5.1: Functional Profile of Chinese PV TIS
Note. A darker shade indicates a more strongly developed function. The heat-map in this figure is based on the calculated net values and normalized values, which are provided in Appendix 9.
Source: Author's own compilation

Coding process resulting the co-occurrence table of the most salient points of the functional system analysis of each solar PV value chain segment. Figure 5.1 depicts the overall assessment of China's PV TIS. Reading the table along a specific column results in a conventional TIS analysis of each segment of PV value chain. It shows that in the downstream segment, the strongest functions are guidance of the search, market formation, and creation of legitimacy, with no major weaknesses compared to other functions. In the midstream segment, strengths lie in entrepreneurial activities, guidance of the search, and legitimation, while knowledge exchange and market formation are relatively weaker. Similarly, in the upstream segment, guidance of the search and legitimation remain key strengths, whereas knowledge exchange and market formation continue to show the weakest performance among the functions in this segment.

Meanwhile, reading each function from left to right gives an initial sense of how evenly innovation activities are distributed across the different segments of the value chain. It also helps identify any areas where progress is lacking or bottlenecks may exist. It shows that the innovation activities are more developed in downstream segment relative to the other segments, although the latter two still show relatively well-performed.

The result indicates that the strongest functions are guidance of the search (F4) and creation of legitimacy (F7). Although China leads the global PV value chain across all segments, which might suggest a strong presence of entrepreneurial activity (F1), the analysis based on coded academic sources shows that entrepreneurial activity is only moderately fulfilled compared to the much stronger performance of F4 and F7. We argue that it is due to China's solar PV development dates back to 1958, and the assessment includes this long timeline. However, as noted by Bai et al. (2024), the rapid growth of PV technology actually began around 2011, which matches findings from IEA (2022) showing that China significantly increased its leadership in manufacturing wafers, cells, and modules between 2010 and 2021. Technically, we argue that those facts help to explain why the function of entrepreneurial activity appears less frequently in the coding results, and therefore the function is relatively less fulfilled compare to the guidance of search and legitimation.

Moreover, we found that functions related to policy direction and legitimacy stand out more in China's PV development mainly because the government and public institutions have consistently played a strong and visible role, more so than individual entrepreneurs. Huang et al. (2016) and K. Li et al. (2018) point out that while many entrepreneurs joined China's PV sector for profit, it was the central government's policy plans that provided long-term direction and official recognition for the industry. This recognition allowed local governments to support PV businesses by mobilizing resources. Similarly, Carvalho et al. (2023) found that China's rise as a global leader in PV manufacturing during the 2010s was largely supported by government subsidies.

The following subsections unpack the resulting figure in two ways: first by examining each function's performance within the upstream, midstream, and downstream segments, and then by evaluating the system's overall strengths and weaknesses.

5.1.1. Overview: Actors and Institutions

China's solar PV development began in 1958, when the first piece of silicon single crystal was invented by Chinese Academy of Sciences (CAS) (Huang et al., 2016). Until 2024, 55 policies regulated solar PV were enforced in China (IEA, 2025). In more than 6 decades, Chinese governments collaborated with research institutions, universities, and industries, both national and international institutions in developing a better solar PV ecosystem. Figure 5.2 illustrates an overview of the major actors and institutions that make up the innovation system in China's PV value chain.

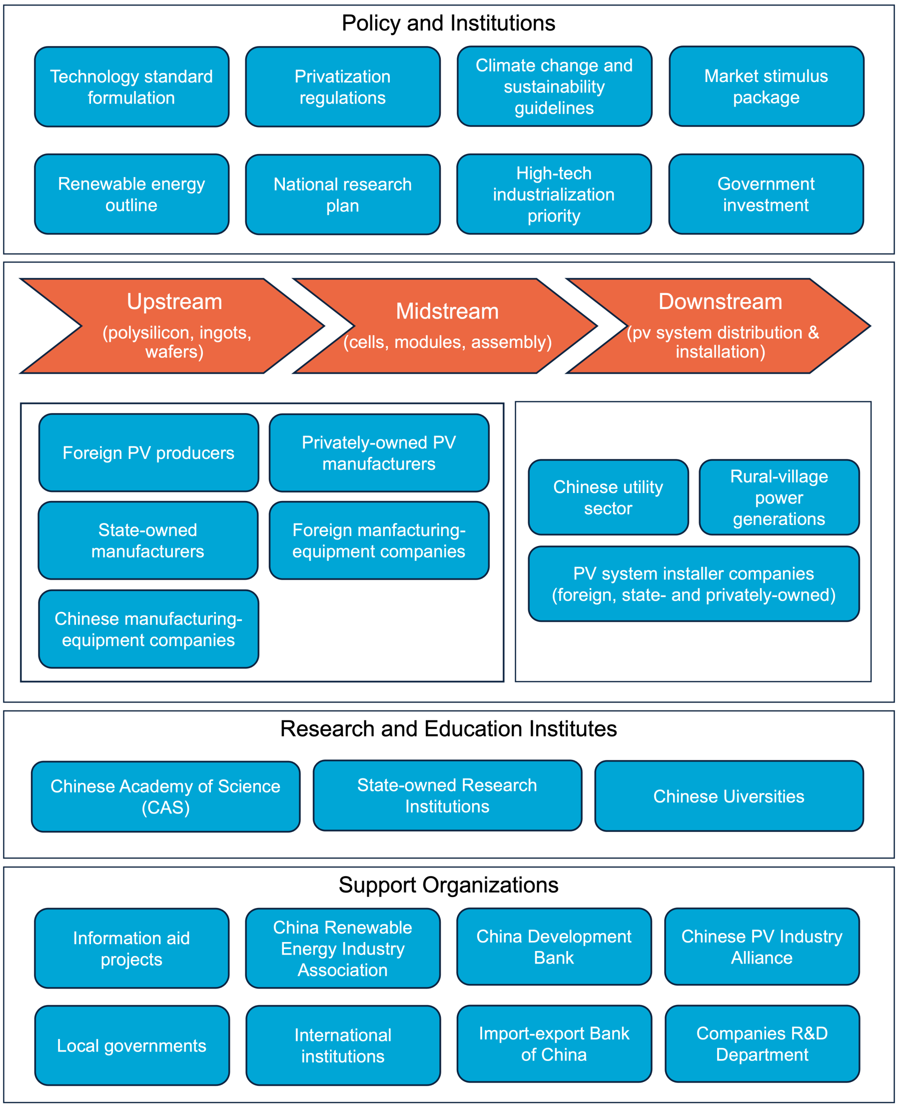

Figure 5.2: Key Actors Mapping
Source: Author's own compilation

Solar PV manufacturing and PV system installation companies are key value chain leaders, serving as both implementers and influencers of strategic interventions shaped by policies and institutions. These actors are categorized into upstream and midstream segments (comprising PV manufacturers and assemblers) and a downstream segment, which includes PV system installers as technology suppliers and solar power generation projects as end users. The innovation system across this value chain is supported by institutions that regulate and facilitate the flow of finance, knowledge, markets, and technology.

Interim Regulation on Private Companies highlighting the first steps of China's openness economy to legitimate rights and interests of privately-owned companies, after before the country was dominated by public ownership businesses as socialist country. This shifting also affected the development of PV sector since it included under the priority sectors (Huang et al., 2016). After the privatization regulations, China's economic has experienced continued and sustained economic growth, which followed by the demand for energy (K. Li et al., 2018). From energy efficiency to renewable energy transitions were planned to achieve energy self-sufficiency (Guilhot, 2022). In short, following by further supports from the government policies in promoting renewable energy and the involvement of foreign and local private entrepreneurial activities in renewable energy sectors make the PV sector development in China's possible (Huang et al., 2016; K. Li et al., 2018). Below, the performance of the innovation functions in every segment of PV value chain and the performance of the functions across all segments will further explore.

5.1.2. Upstream

The innovation system in this particular segment has been moderately developed as all functions fulfilled in quite light colours relative to the other two segments that considerably well-developed. Creation of legitimacy and guidance of search functions mark as the strongest ones within this segment. It's dominating by a strong PV technology and renewable energy promotion by the actors or institutions as well as strong policies and regulations.

A shift from a centrally planned socialist economy towards a more open, got a government's legitimation through the establishment of Interim Regulations on Private Companies (F4-a)[1]. Since then, privately-owned entrepreneurial activity has officially been allowed and even encourage in certain sectors (F7-c), including the manufacture and generation of PV (Huang et al., 2016). International guidance and events (F4-a) also play a key role in upbringing solar PV technology to the country, through environmental focus and renewable energy development. For instance, the United Nations Framework Convention on Climate Change (UNFCCC), that translated by the Chinese Central People's Government (CPG) to the encouragement of renewable energy technologies (F7-c), which PV was included (Huang et al., 2016). To see the government commitments in prioritizing the development of this technology, several nationwide documents and programs were created mentioning solar PV technology, including the 10th China's Five-Year Plans (2000-2015), the 'Plan for New Energy and Renewable Energy Industry Development' marked the beginning of China's interest in solar PV technology (Bai et al., 2024; Guilhot, 2022; Huang et al., 2016); Top Runners Bases program (Y. Zhang et al., 2021); the 863 Program and Peacemaker Plan (Bai et al., 2024); and some more including the incentive policies, industrial adjustment and standard development, and energy law.

Vital support provided by the central and local government through a decentralized implementation, local policies were directly aligned with the central government policy. For example, while the central government identified PV industry as one of a number of key industries under the Catalog of Chinese High-Technology Products for Export (F7-c), local governments had a strong incentive to facilitate the growth of local PV industries and granted them preferential treatment (F6-a) (Y. Zhang et al., 2021). Several financial-incentives scheme were introduced and adjusted (F6-d) to support PV enterprises, such as direct project subsidies, tax allowance, feed-in tariff, credit low rates, and government investment (Bai et al., 2024; Guilhot, 2022; Y. Zhang et al., 2021).

Other activities that positively affecting the development of upstream segment in China's PV value chain are entrepreneurial activities and knowledge development. In entrepreneurial activities, there are growth of companies production capacity and companies that entering polysilicon and wafers market. In the early stage, silicon materials and ingots were heavily rely on import (F3-d), because it requires much higher purity than for semiconductor chips (Bai et al., 2024; Huang et al., 2016), allowing for knowledge diffusion in the development of upstream industries. Eventually, as shown in Figure 5.3, the production capacity of Chinese polysilicon manufacturing were increased over the years (F1-c), reaching over 90% of global production capacity in 2024. Most of the major polysilicon manufacturers use the Siemens process, with more than 98% polysicilon is used for photovoltaic solar and the rest for semiconductor chips, meaning that there are two market segments that can absorb polysilicon production. Government support policies and incentives mentioned above, attracted new company investment and promoted the rapid growth of PV industries (F1-b), inclduing polysilicon and wafers

[1] The code format "*F(number)-(letter)*" is used to connect each function with the most frequently occurring code related to it. The full list of these codes is provided in Appendix 9. For example, "F4-a" indicates that Function F4 – Guidance of Search – is most often supported by event "a," which refers to clear regulation and policy.

manufacturers (Bai et al., 2024; Huang et al., 2016).

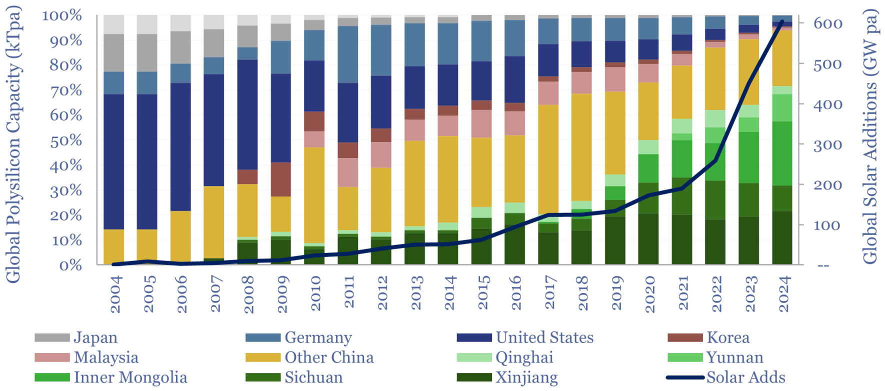

Figure 5.3: Global Polysilicon Production Capacity
Source: TSE (2024)

Though the companies and pruduction capacity are growing, some of the companies also encountered period of struggling and bankruptcy (F1-e). According to Bai et al. (2024), Huang et al. (2016), and Zhao et al. (2015), a global financial crisis in 2008 following with European crisis in 2009, resulted in the deceleration of global PV demand in 2011 (F5-f). The worse point is when EU and USA imposed the anti-dumping and anti-subsidy duties in 2012 (F5-g), caused in no growth in China's polycrystalline silicon and PV cell production output (F1-e). And therefore, some Chinese PV companies were struggling and found bankruptcy such as Trina Solar and Suntech Power (F1-e). As shown in Figure 5.3, the growth rate of the production capacity and output of polycrystalline silicon has shown a clear reduction since 2010. Therefore, in the demand creation function in this segment showing a relative small value of co-occurence. Even if there are domestic demand creation activities to absorb the production output, yet, global market situation also affecting this segment.

5.1.3. Midstream

System functions in midstream segment performs relatively better compare to the upstream. All functions are fulfilled with slightly dark shades, meaning that most of the activities are positively supporting the development of PV technologies. The strongest performance can be seen in creation of legitimacy, guidance of search, and entrepreneurial activities.

In this segment, strong support for PV technology and renewable energy, along with solid policies and regulations, are frequently mentioned in the main papers. The scores are slightly different from those in the upstream segment, but not by much, which can be seen in the Appendix 9. This is because most policies and programs are written in broad terms, they cover the entire PV value chain, including polysilicon, wafers, cells, modules, and PV systems. Some documents highlighting particularly the development of PV cell modules and machinery technology, such as the 'New Energy and Renewable Energy Development Outline for China (1996-2010)' that was drafted by the National Scientific and Technological Commission (NSTC) (Huang et al., 2016).

Additionaly, more information on the companies that entering solar cell and module market as well as manufacturing equipment growth in the country. Generally, China has witnessed active new entries and a significant number of firms for each product in solar PV value chain. The sector is largely privately-owned and profit margins are the central factor to drive the firms' market entry or exit decisions (L. Zhu et al., 2019). The first privately-owned PV companies established in 1999 (F1-b), which mainly relied on previous capital accumulation by entrepreneurs rather than investment by the government or capital market (F6-d), as well as relied in imported PV machinery and technologies (F3-d) (Huang et al., 2016). High profitability and short payback period of solar cell production (often under a year) motivated many Chinese PV manufacturers entered the global market with a competitive edge in lower production costs (more efficient compared to other countries (F1-c)) (Huang et al., 2016). By 2007, China overtook Japan and the EU to become the world's top producer of PV cells (F1-c) (Bai et al., 2024; Huang et al., 2016). Further, not only the production of solar cells and modules that constantly developed and acquired global market, Chinese PV machinery manufacturers also began exporting (F1-a) PV machinery to foreign PV manufacturers in 2010 (Huang et al., 2016).

More activities supporting the development of PV technologies in midstream segment including resource mobilization, knowledge development, market formation and knowledge exchange. Not only government that provides financial support to develop PV technology, private sectors as well. For instance, some entrepreneurs mobilize their capital accumulation to develop factory plant (Huang et al., 2016). State-owned enterprises plays key important roles in initiating the diffusion and development of solar cells/modules and manufacturing equipment technologies. Initial technology import and research initiated by SOEs such as, the first solar cells manufacturing and application in space satellites in 1968 (F2-a), imported manufacturing equipment from US and Canada by SOEs and research institute in 1979-1992 (F3-d), and the 48th Research Institute of China Electronics Technology Group Corporation (CETC) – a key research and production enterprise, which built twenty c-Si solar cell production lines for Chinese PV solar cell manufacturers (F1-c) and largely consisted of self-developed PV machinery (F2-b) (Huang et al., 2016). It is align with Carvalho et al. (2023), that suggests that Chinese companies mostly acquired PV technologies by purchasing production equipment from international suppliers (F3-d).

5.1.4. Downstream

Finally, compare to the the other two segments, the downstream segment relatively has the strongest overall system functions, as all functions relatively has darkest colours. Guidance of search, market formation, creation of legitimacy, resource mobilization, and knowlesge development are dominating the activities in developing PV technology in this segment. Meanwhile, entrepreneurial activities and knowledge exchange are moderately developed relative to the other functions.

The guidance of search dominating by many policies and regulation as well as target/visions targeting this segment. For instance, China's energy policy from 1981 to 2020, marking the 6th-13th FYPs (F4-a), was moving from energy efficiency target to renewable energy target (F4-c), guiding towards the application of PV system to achieve energy mix target and lower carbon internsity (Guilhot, 2022). Other than that, the Brightness program was the fist national policy formulated by Chinese governmen to bring electricity to remote areas by means of renewable energy (S. Zhang et al., 2014). Following with Township ELectrification Program in late 2002 which part of the Brightness Program, to scaling up solar PV deployment, including off-national grid, stand-alone and micro-grid systems (S. Zhang et al., 2014). More example, including Golden Sun Demonstration Program, Rooftop Solar Subsidy Program, solar PV concession programs, Top Runners Bases Program, the 531 policy, and more (Bai et al., 2024; S. Zhang et al., 2014; Y. Zhang et al., 2021). Those programs and policies targeting the distribution of electricity, which eventually creating domestic demand for PV system installation (F5-a). Such policies and programs include market stimulus and incentives (F5-e), such as feed-in tariff (FIT), attracting more businesses to invest in the PV installation projects. As Guilhot (2022) explained that FIT is the most influential policy in China's PV development, has played a key role ib driving market throughout the initial stages.

Creation of legitimacy, again, supported by strong PV technology and renewabe energy promotion from the government. Since there are many programs and policies targeting more PV installation capacity, so does the government encouraging the development of downstream segment by explicitely mentioning (F7-c) the technology in the national documents. Such as through Electric Power Act document, through convention event, etc. (Huang et al., 2016). Moreover, a lobby for new policy programs stimulating local demand (F7-a) for PV emerged between 2004-2008, and continued in 2009 with greater effort from the Chinese entrepreneurs and local governments, resulting the establishment of Chinese PV Industry Alliance in 2010 and an inclusion of PV technology under the seven Strategic Emerging Sectors (SES) (Huang et al., 2016). This lobby process in the demand side of PV brought down the prices of solar PV close to the coal-fired electricity, and therefore, eventually affecting the growth in the PV manufacturing industries to serve the domestic market (L. Zhu et al., 2019).

Financial resource mobilization and decentralized implementation from national to local government also dominating this segment development. Meanwhile, there are more variance in knowledge development activities including active R&D projects and investments, demonstration and pilot projects, as well as leaning activity through learning by doing and internal technology advancement. For example, in 2002, a peak investment with total expected value at USD 0,2 billion mobilized by the Chinese government to covered electrification program in 783 rural villages using renewable energy sources, including PV generation (Huang et al., 2016). Investment also allocated in the R&D project and demonstration project, such mentioned by Bai et al. (2024). Interestingly, learning activities in China's case not only correlated with the activity of developing the physical technology, but also in the policies. The governments actively reflecting the implementation of solar PV programs and policies (F2-c), learning from the problems occurred in he previous stage, to improve the quality of the policies and programs following the recent situation (Y. Zhang et al., 2021).

Nevertheless, Zhi et al. (2014) found that China was often introduced policies in response to external pressures such as global market trends or foreign policy models (such as Germany's FIT system), and reflect policy learning by imitation rather than being guided by research-based strategies. China's PV policy continues to depend heavily on government intervention, indicating that market mechanisms have not functioned as intended. Since 2009, China has made progress in creating demand-side solar policies like FITs and public demonstration projects. However, its solar market still depends heavily on government control rather than open market mechanisms. Unlike Europe, US, or Japan, where solar users can sell electricity at market prices, China sets fixed prices through government policy. This makes it easier to manage but limits competition and market efficiency (Zhi et al., 2014).

5.1.5. Overall functional profile of the TIS

The overall functional profile of the TIS shown in Figure 5.1 reveals a robust and maturing innovation environment across China's solar PV value chain, with notable variations by segment. Factors support the development of China's solar PV in every value chain including

1. Guidance of search (F4) and Creation of Legitimacy (F7)
   Overal, system functions in China's PV value chain shows a clear policy direction and institutional support for solar PV technologies. According to Zhi et al. (2014), before 2006, China's PV policies primarily targeted local governments, instructing them to meet set goals, develop detailed regulations, prepare production conditions, and oversee the planning and execution of demonstration projects. Starting in 2006, policies began focusing on PV R&D and manufacturing enterprises, offering direct financial support for research, production, and tax incentives for high-tech companies, as well as access to national laboratory resources and renewable energy funding. From 2007 onward, policies also extended to power companies, supporting the PV industry through measures such as FIT subsidies, trading mechanisms, standardized pricing, and guaranteed full-purchase of renewable electricity.
2. Market Formation (F5)
   Market formation is particularly strong in the downstream and relatively moderate in the other segments, showing successful stimulation of demand, especially at the end user (downstream segment: solar PV installation and application).
3. Resource Mobilization (F6)
   This function is well developed across all segments, indicating the availability of capital, infrastructure, and skills necessary to sustain growth in the overall PV value chain in China.
4. Entrepreneurial activities (F1)
   This function is active across all segments, with strong engagement especially in the midstream. This indicates a vibrant innovation climate driven by both established firms and new entrants.
5. Knowledge development (F2) and diffusion (F3)
   Chinese PV manufacturers primarily gained their technological capabilities and expertise through the importing of manufacturing equipment and the recruitment of experienced executives, many of whom were part of the Chinese diaspora and played key roles in establishing early PV enterprises.

Meanwhile, some challenges that China encountered during the development process, including:

1. Global market dynamics
   A persistent market risks or instability market formation occur in all segment, especially in the midstream segment. Global market dynamics are the main challenge for market creation and entrepreneurial activities to be well-performed. Thus, an agile demand-side policies are applied in China, such as FIT and subsidies.

2. Academic and practical research gap
   Knowledge barriers and confusion effects are still present but with minimal effects. For instance, there was a wide gap between academic R&D related to new PV technologies and the application of this knowledge by PV manufacturers in China in early 2000s, causing entrepreneurial activities were not greatly influenced by the strengthening knowledge creation in the academic settings. Yet, this effect was substituted by the strong interaction between foreign PV producers and China, and interaction inter-sector industries (e.g. between photovoltaic and semiconductor sectors) (Huang et al., 2016).

5.2. Design Factors Analysis

This analysis examines empirical data on how China has developed its solar PV manufacturing based on influencing factors formulated by Macé et al. (2023). Given that the value chain is already well-developed, the focus of this section will be on interpreting and analyzing the current implementation and the development process. This section will be devided into four sub-sections representing each category for the design factor.

5.2.1. Baseline requirements

Table 5.2: Key Factors Influencing China's Solar PV Manufacturing Development

Factor	Findings
Existing industrial ecosystem	Fragmented PV manufacturers area: • Upstream manufacturers: resource-rich regions with plentiful silicon reserves & low energy cost. • Midstream manufacturers: coastal provinces, with strong logistics networks, skilled labor, and proximity to major domestic & international market. • Downstream PV system installers: urban centers with high energy demand & supportive local policies for RE (hubs for solar system deployment).
Existing upstream PV actors	Initially relied on imports for 95% of its polysilicon (only two domestic firms produced 400t in 2005), but state-backed industrial policies quickly expanded upstream capacity, turning this bottleneck into a competitive strength and making Chinese manufacturers dominant across the PV value chain.
Infrastructure readiness	China kept the dense coastal hubs such as Shanghai, Jiangsu and Zhejiang that used agglomeration, shared ports, suppliers, and logistics networks to cut shipping costs and help PV production grow quickly.
Availability of raw material	Two-folds key raw material strategy: • China produces most of what it can at home, about 79% of the world's silicon and 59% of its aluminum. • China uses state-backed loans to secure metals it lacks, such as copper, from overseas mines (about $13 billion has gone to copper-cobalt projects in the DRC), while staying in control in the processing stage.
Domestic solar demand	China made solar PV as an important industry and backed it with a clear set of domestic policies, resulting a steady growth of PV domestic demand to 217 GW in 2023. It gave its manufacturers a reliable buyers, let them scale up, and pushed constant innovation, leading to economies of scale.
Ease of doing business	China's broad "ease-of-doing-business" reforms, such as one-stop company registration, faster permits and utility connections, renewed contract documents, and clearer investor protections, created a business-friendly environment that policies like Jiangsu attract over a thousand PV firms. Straightforward rules and quick services at both national and local levels gave solar manufacturers the confidence to invest, cluster, and scale up fast.

Source: Author's own compilation

The baseline requirements reflecting the fundamental conditions that are necessary to determine a suitable location to develop PV manufacturing site. Table 5.2 depicts the findings from China's efforts in fulfilling its baseline requirements to build PV manufacturing sector. In China, solar PV manufacturing capacity is concentrated in a few provinces and autonomous regions, which are areas granted a certain level of self-governance by the central government, in order to minimize the cost of production and logistic (Zissler & Ishida, 2024).

China's polysilicon, wafers and various metals manufacturers are located in resource-rich regions which offer plentiful silicon reserves and low energy costs, making them key production hubs (Wang & Liu, 2024). It scattered among the center part of China like Yunnan, Inner Mongolia, Ningxia, and Sichuan, as well as the northwest part in Xinjiang (Wang & Liu, 2024; Zissler & Ishida, 2024). Conversely, according to Wang and Liu (2024), midstream operations are more geographically dense, reflecting the capital-intensive and efficiency-driven nature of this manufacturing stage. This segment, includes most equipment manufacturing such as solar cells and module assembly, is predominantly concentrated in coastal and eastern provinces—particularly Jiangsu, Zhejiang, Guangdong, and Anhui (Wang & Liu, 2024; Zissler & Ishida, 2024). These regions benefit from strong logistics networks, skilled labor availability, and proximity to major domestic and international markets. For instance, Jiangsu stands out as a central hub, hosting numerous manufacturers that specialize in cell production and module integration, reinforcing its strategic role in the national PV supply chain (Wang & Liu, 2024). Lastly, the downstream segment is more geographically decentralized compared to upstream and midstream activities. It typically clusters in urban centers where energy demand is high and local policies support renewable energy adoption. Major cities such as Beijing, Shanghai, and Guangzhou have become important hubs for solar system deployment, driven by supportive local governments and increasing public awareness of sustainable energy solutions (Wang & Liu, 2024). Figure 5.4 depicts the distribution of the PV manufacturing cites.

Figure 5.4: Map of Main Provinces and Regions for Solar PV Manufacturing
Source: Author's own compilation based on data from Wang and Liu (2024) and Zissler and Ishida (2024)

Incumbent PV industries, particularly in the upstream segment can enhance supply chain partnerships and as a proof that players from the same industry have managed to set up a local manufacturing activity (Macé et al., 2023). According to J. Li and Ma (2009), the production of polysilison has been the cause of China's bottleneck situation in the industrial chain. When China first began manufacturing solar PV products, they had to import 95% of its PV feedstock for solar cells production, due to a lack of advanced technologies for producing polysilicon. There was only two companies that produce high purity silicon in 2005, namely Ermei Semiconductor and Louyang Zhonggui with total production capacity 400 tons (J. Li & Ma, 2009). As mentioned by Gang (2015), although China had abundant silicon reserves, it fell behind internationally in silicon purification during the mid-2000s. This was largely due to outdated technologies and weak environmental regulations, which led to high energy use and the release of toxic waste. Thanks to the Chinese state of capitalism model, which many manufacturing industries are backed by proactive government policies, solar PV production has long featured the highest localization rates for its equipment, the lowest technological threshold, the largest number of small- and medium-sized businesses, and the greatest expansion in the global PV manufacturing industry. Figure 5.5 depicts the growth of upstream industries since 2001 to 2008, while Table 5.3 shows current top 10 PV companies that are dominating by Chinese manufacturing.

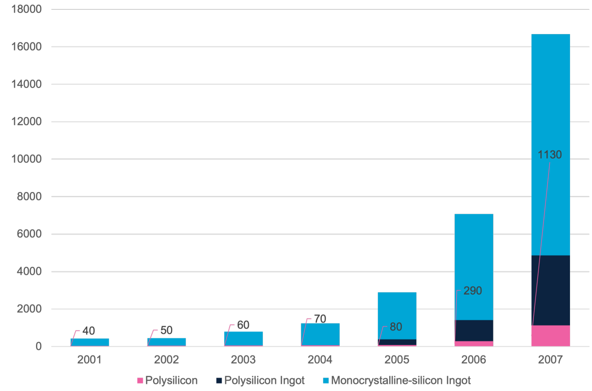

Figure 5.5: China Polysilicon and Ingot Production, 2001-2007
Source: J. Li and Ma (2009) and Martinot (2007)

Table 5.3: Top 10 Polysilicon Companies, September 2024

Ranking	Company	Country Ownership	Manufacturing Capacity (GW)
1	East Hope	China	103
2	Xinte Energy	China	100
3	Tongwei	China	90
4	Daqo New Energy	China	68
5	GCL Technology	China	67
6	Wacker Chemie	Germany	32
7	Asia Silicon	China	30
8	Wuhan Dongli	China	20
9	Xinjiang Goens Energy Technology	China	20
10	Hoshine Silicon Industry, Ningxia Baofeng Energy, Qinghai Lihao Semiconductor Material, Suzhou Runergy PV Technology, Trina Solar, and Xinjiang Jingnuo New Energy Development	all China	each 17

Source: Zissler and Ishida (2024)

China maintains a competitive logistics system, ranking 19th in the 2023 World Bank Logistics Performance Index (LPI), while Hong Kong SAR ranked 7th (https://lpi.worldbank.org). According to Wang and Liu (2024), the early growth of China's PV manufacturing was strongly influenced by proximity to both suppliers and markets. Key industrial areas such as Shanghai, Jiangsu, and Zhejiang became central hubs due to their established infrastructure and access to global trade routes. This arrangement helped lower production costs and improve export logistics. As the industry developed and domestic demand expanded, manufacturing gradually spread to nearby regions, reducing reliance on a few locations and making the sector more resilient to global market changes.

China's still dominating some of the main minerals production used as key materials for PV manufacturing. According to Zissler and Ishida (2024), in 2023, China made about 79% of the world's silicon metal, which showing a very high share. China also led in aluminum smelter production, making around 59% of the global total. In contrast, silver and copper production were more evenly spread out across different countries and not heavily concentrated in one place. We will take a look on a broader mineral transition in China, where Beijing becoming a major source of financing for projects around the globe that involve particular minerals, like copper that needed to facilitate solar PV manufacturing and energy transition in general. Although China contributed to 44% copper refinery production (Zissler & Ishida, 2024), it only has 3% of global Copper reserves (Escobar et al., 2025). According to Escobar et al. (2025), China effectively spends money to buy raw materials from other countries because it doesn't have enough of them at home. At the same time, China stays in control of the more advanced steps in the supply chain, like processing the materials and making finished products. For instance, Beijing has directed about 83% of its official financial support toward copper mining and processing projects. Between 2000 and 2021, Chinese state-owned lenders approved 19 loans worth around $12,85 billion for cobalt and copper mines in the DRC. Some of the world's biggest cobalt and copper mines, like Tenke Fungurume and Sicomines, are in the DRC and are run by joint ventures between Chinese and Congolese state-owned companies (Escobar et al., 2025). This strategy lets China import the raw material from foreign mining extractions while keeping the higher-value refining and manufacturing stages inside the country.

China's demand for solar energy grew quickly, increasing its share of global new installations from 12% in 2012 to almost 45% in 2016 (IEA, 2022). In 2023, it installed 216.88 GW of new solar PV capacity, marking a 148.12% increase compared to the 87.41 GW added in 2022 (Shaw, 2024). This steady growth happened because, in the early 2000s, the Chinese government chose solar PV as an important industry to grow its economy and boost exports, resulting in economies of scale and continuous innovation across the supply chain (Wang & Liu, 2024; Zissler & Ishida, 2024). As a result, the cost of solar PV dropped by over 80%, making it the cheapest way to produce electricity in many parts of the world (Wang & Liu, 2024).

China ranks 31st globally on the ease of doing business rankings with a score of 77,9 out of 100. According to World Bank (2019), China has made several important reforms to make it easier to do business in the country. These include setting up a one-stop system for business registration and company seal issuance, simplifying building permits for low-risk projects, and speeding up access to water and drainage services. The process to get electricity has been streamlined, with clearer information on tariff changes. Investor protection has been improved by holding major shareholders accountable for unfair deals and making ownership structures more transparent. The government also introduced lower taxes for small businesses, reduced VAT for some sectors, and improved online tax filing. Trade processes were simplified by allowing early cargo declarations, upgrading ports, improving customs procedures, and publishing clear fee schedules. Legal processes have become more efficient by limiting court delays and setting clearer rules for bankruptcy, including better creditor involvement and rules for financing during insolvency. A clear example of the effect of the reformation in ease of doing business can be seen in Jiangsu province, which has become a major hub for solar PV manufacturing, hosting over 1176 companies, as a result of the province's proactive industrial policies, strong R&D support, and favorable business conditions (Wang & Liu, 2024). The growth in Jiangsu shows how national-level reforms, when matched with effective local initiatives, can attract large numbers of enterprises and drive sectoral growth.

5.2.2. Key requirements for CAPEX-intensive Industries

The key requirements for this step reflecting the need for capital availability to support the capital-intensive industries, such as polysilicon and wafer manufacturing. Table 5.4 depicts the findings from how China mobilizes its capital to support industries.

Table 5.4: Capital-Driven Factors Influencing China's Solar PV Manufacturing Development

Factor	Findings
Access to capital	China's solar factories took off because money was cheap and sales were guaranteed, where state banks offer large amounts of money with low-interest loans, tax breaks, and subsidies, while feed-in tariffs and auctions ensured companies could sell their panels.
Interest rates	China kept its lending rates below 4% through its state-owned commercial banks, while other big economies saw theirs climb, so Chinese solar-panel makers could borrow money cheaply.

Source: Author's own compilation

One of the competitiveness sources from China's PV manufacturing over other countries is the government support in providing capital. This government support includes public equity stakes in private corporations and state-owned enterprises, state subsidies and tax incentives and finance from export credit agencies as well as central banks. Feed-in tariffs and auctions for solar PV have been introduced in 2011 and 2019, respectively, to create demand in the PV sector (Zissler & Ishida, 2024). According to International Energy Agency (2024), other than capital support from the government, commercial sector also contributed roughly 73% of energy investments overall, including equity investments made by private enterprise and households, alongside debt from financial institutions. Commercial finance also includes some finance from state-owned banks, sovereign wealth funds and pension funds, although this includes a degree of state-directed lending, especially in emerging economies with strong industrial policies. The state banks have provided grants and low-cost loans since the mid-2000s, in order to support the PV manufacturing sector from the supply side (Zissler & Ishida, 2024). In 2009 and 2010, the China Development Bank (CDB), a state policy bank, offered around USD 30 billion in credit lines to support its solar cell and module producers (Huang et al., 2016).

Higher interest rates generally make loans more expensive for borrowers, investors then demand a higher potential return from riskier investments like stocks (equity). As a result, higher interest rates can lead to a downward pressure on stock prices, as companies might find it harder to justify their valuations if investors are demanding higher returns. Between 2020 to 2024, the People's Bank of China, as well as other state-owned commercial banks, have continued to lower their interest rates to stay almost flat below 4%, in contrast to the upward trend in most other major economies (International Energy Agency, 2024). Because money stays cheap, Chinese solar PV producers can raise capital at lower cost, helping them build factories and projects more easily than rivals in higher-rate countries.

5.2.3. Key requirements for OPEX-intensive Industries

This requirements reflecting on how is the availability of hard and soft infrastructure can reduce the operational cost of PV manufacturing activities in China. Table 5.5 shows the findings from China's strategy in providing affordable electricity cost and supply, carbon intensity, and labor cost.

Table 5.5: Cost-Driven Factors Influencing China's Solar PV Manufacturing Development

Factor	Findings
Electricity cost & supply	China kept industrial power costs low (about $0,07 /kWh) with 61% sourced from coal-fired electricity.
Carbon intensity	China has cut coal's share of its power mix by 16% since 2010 as wind, solar, and hydropower have grown. Provinces like Qinghai and Yunnan provinces with lots of hydropower, are now attracting companies that make solar panels.
Labour costs	China's early solar-panel boom was driven by very low factory wages. While labour contributes under 10% of a total cost and helped the industry scale fast, this factor can kick-start PV manufacturing, but as the sector grows, success depends more on capital and advanced technology than on labor costs alone.

Source: Author's own compilation

Chinese solar PV industry benefits from affordable electricity prices. In 2023, electricity prices for large industrial customers in energy-intensive industries were around $0,07 per kilowatt-hour in China, which was slightly more than in the United States ($0,06/kWh) but still much lower than the European Union average of $0,11/kWh (Zissler & Ishida, 2024). A large portion of this electricity, about 61% came from coal, which helps keep prices low even though raises environmental concerns.

On a positive note, coal's share in electricity generation has dropped by 16 percentage points since 2010, mainly due to the growth of renewable energy sources like wind (both onshore and offshore), solar PV, and hydropower (Zissler & Ishida, 2024). In China, provinces such as Qinghai and Yunnan stand out for their cleaner energy mix, especially from hydropower, making them attractive locations for industry. As a result, many large manufacturers are now relocating their polysilicon and wafer production from higher-emission areas like Xinjiang to these lower-carbon regions (IEA, 2022).

Much of China's early expansion of manufacturing sectors can be attributed to its competitive advantages in cheap labour and land, besides the good infrastructure and the alleged undervaluation of the CHinese currency (Gang, 2015). In 2022, China has the lowest manufacturing labour costs, compare to ASEAN countries, India, US, Korea, and Europe (IEA, 2022). According to Gang (2015), labour only formed less than 10% from total production costs, making it a crucial factor in determining PV manufacturing competitiveness only in the early stage, while capital- and technology-intensive industries become markedly more important along with the CHina's economic growth.

5.2.4. Key requirements for competence-intensive industries

Finally, this step reflects the requirements for high-technology or innovation-driven in PV manufacturing development. Table 5.6 shows the China's strategy in providing qualified labor, R&D centers and the availability of IP in order to drive the innovation within PV sector.

Table 5.6: Innovation-Driven Factors Influencing China's Solar PV Manufacturing Development

Factor	Findings
Availability of qualified labour	Manufacturers lured thousands of local PhDs with attractive pay (around USD 61.000 a year) and built up a large, highly trained workforce between 2004-2008.
R&D centres	China couples strong public R&D funding with industry-run laboratories.
IP availability	China holds the world's largest pool of PV patents, with leading firms forming dense, stable collaboration networks that keep most new intellectual property inside the country.

Source: Author's own compilation

Between 2004 and 2008, in the period of boosting PV manufacturing sector, Chinese PV manufacturers built a large, skilled PV workforce by combining aggressive recruitment of local PhD graduates by offering salaries of about CNY 500.000 per year (about USD 61.000) (Huang et al., 2016). According to IEA (2022), currently the majority of skilled personnel is based in China and Southeast Asia, therefore any country that wants to grow its own PV manufacturing must scale up similar training and education efforts to ensure enough qualified workers are available from day one.

China couples strong public R&D funding with industry-run laboratories. PV technology was included in the three most significant national research programs in China during 2000–2001, namely the 'National Basic Research Program of China (973 Program)', the 'National High Technology Research and Development Program of China (863 Program)', and the 'Plan of National Key Science and Technology (2001–2005)' (Huang et al., 2016). Moreover, "Made-in-China 2025" agenda pushes provincial governments to co-finance smart manufacturing parks and R&D facilities to maintain competitive advantages in PV manufacturing sector (Wang & Liu, 2024). Commercial sector also brings contribution to the innovation in PV sector. Up to 2009, there have been more than 500 solar PV firms and R&D labs in China actively pushing the frontiers of related technologies (Fu & Zhang, 2011). Leading companies such as Trina Solar operates state-key laboratory and partner with top universities to trial new materials, high-efficiency cells and module designs, showing how enterprise-led centers drive continuous PV innovation (Hu et al., 2024; Trina Solar, 2024).

According to Hu et al. (2024), China has held the top position globally for PV patents since 2012, reflecting its strong focus on solar innovation, although there are still gaps in some key areas like ethylene vinyl acetate (EVA) film, highlighting the need for continued R&D efforts. Major companies such as CSI Solar, JinkoSolar, and Aiko Solar Technology have played a key role in driving innovation and developing new PV technologies. Among patent applicants, those with investment-based partnerships tend to dominate collaboration networks. In addition, more provinces are now actively involved in PV technology innovation, with the most influential innovation hubs still concentrated in a few regions, mainly the eastern coastal provinces, which continue to lead in technological advancement.

5.3. Driving Forces Analysis: Institutional Context in China's Solar PV Value Chains Development

This step of analysis will be aligned with the driving forces concept in the multilayer analytical framework, which consist of International Institutions, FDI, Country-Level Strategy, and Regional Institutions in regionalizing solar PV value chain. How each institution rule out the development of solar PV value chain in China will be explored. However, since the point of view from this analysis is from Chinese case as one country entity, therefore we will analyze China's participation in the bilateral/multilateral regional cooperation to build regional value chains.

To support its own development and keep up with fast-paced globalization and regional cooperation, China has taken a more active role in international organizations. In 2013, China introduced the Belt and Road Initiative (BRI) to build new supply chains and strengthen regional value chains. Through the BRI, China aims to lower cross-border logistics costs, boost economic growth, and attract more investment and industry transfers (Jianping et al., 2020). According to X. Zhu et al. (2023), Chinese solar companies tend to expand into countries that already have trade ties with China under the BRI. The BRI itself plays a key role in building these trade connections and is influenced by partner countries' features such as openness, GDP per capita, and institutional quality. As a result, Chinese solar PV exports have become concentrated in fast-growing regional markets like ASEAN and South Asia, where they hold market shares of 9,33% and 6,59% in 2016, respectively (Shuai et al., 2018). In other side, BRI partnerships will help countries partners, which mostly global south, to upgrade their technology and improve their place in value chains by promoting industrial cooperation and reducing trade and investment barriers (Jianping et al., 2020). For example, in 2014 China's official financing for transition minerals reached over $12 billion, including $0,25 billion in loans for copper mining projects in countries like the DRC (Escobar et al., 2025).

International organization influencing China's PV manufacturing sectors by setting and harmonizing global standards that build trust across markets. For instance, China's entry into the World Trade Organization (WTO) gave its products wider access to international markets and removed many trade barriers (Huang et al., 2016). This led to a sharp rise in China's solar PV production capacity, better product quality, and lower prices (S. Zhang et al., 2014). Similarly, international agreements like the Kyoto Protocol in 1997 encouraged countries to cut greenhouse gas emissions and promoted the use of renewable energy, pushing members to adjust their national rules. As a result of this kind of norm also drives the country member to aligning its national regulation. According to World Economic Forum (2025), China aligns its own "Basic Guidelines for Corporate Sustainability Disclosure" with standards released by International Sustainability Standards Board (ISSB) as a communication bridge with global stakeholders. Furthermore, it gives ***foreign investors*** confidence in Chinese companies' environmental and governance practices. These examples highlighting how the international rules and norms help guide national regulations, support global standardization, and influence where and how investors choose to invest.

Furthermore, foreign investment has been a key part of China's opening-up strategy to build a more modern and globally connected economy. Other than the market potential that attract foreign companies to invest in China, the central government also actively setting up the environment to attract foreign investment. For example, the National Development and Reform Commission (NDRC) has stressed the need to accelerate innovation and upgrade national industries to attract foreign companies (Bega & Lin, 2023). China also regularly releases the Guideline Catalogue of Industries for Foreign Investment, which helps guide foreign capital into specific regions and sectors, supporting industrial growth, technological advancement, and economic restructuring (Jianping et al., 2020). In 1998, solar PV was included in the national Directory of Key Development Industries, Products, and Technologies Encouraged by the Country. At the same time, policies were introduced to exempt import taxes on equipment containing essential technologies for solar cell production, especially for foreign-invested projects, which also received value-added tax exemptions (Zhi et al., 2014). Continuous to 2003, the Ministry of Science and Technology and the Ministry of Commerce released a new directory encouraging foreign investment in the production of PV components such as modules, inverters, and controllers (Zhi et al., 2014). As a result, during the 1990s through 2003, several major international solar companies (such as BP, Shell, Siemens Solar, Sharp, Sanyo, and SEC) entered China, anticipating strong market growth (S. Zhang et al., 2014).

According to Fu and Zhang (2011), many of China's leading solar PV companies began by receiving technology from abroad through licensing deals and joint ventures with MNEs, and had set up over 1,200 R&D centers in China by 2008. In addition, in the earliest stage of PV manufacturing in China, most companies imported turn-key technology from abroad, mainly from Germany which significantly facilitated the production of PV modules (Huang et al., 2016). The technology import was hardly had any influence on China's ability to produce PV technology, but merely served as a means to train a group of people destined to become key technical staff members, and therefore, it is important to couple with an industry's own in-house R&D effort to enhance innovation in domestic firms (Fu & Zhang, 2011; Huang et al., 2016). To make better use of foreign technology, China introduced several policies to encourage stronger connections and knowledge transfer between foreign and local companies. As Fu and Zhang (2011) called as two-leg forward strategy–localized innovation is a prerequisite for developing domestic absorptive and creative capabilities to ultimately benefit from transfer mechanisms.

The country-level strategies in optimizing knwledge diffusion, including the State Council that introduced new measres to improve the managementof foreign invesment in 2018, aiming to create a moer open fair, and high-quality investment environment (Jianping et al., 2020). These efforts also focused on directing investment toward less-developed central, western, and border regions by improving local infrastructure and boosting regional economies. At the same time, China has steadily increased its capacity to absorb new technologies by significantly raising R&D spending, averaging 19% annual growth since 1995, and actively promoting science and research careers among its youth, more so than countries like India and Brazil (Fu & Zhang, 2011). A key turning point came in 2009, when several domestic machinery firms successfully shifted into PV manufacturing, producing c-Si solar cell equipment at much lower costs. As a result, around 70% of the machines used in China's PV cell production were locally made. This reflects China's broader strategy of using state-led support through R&D funding, policy direction, and industrial guidance to drive both technological innovation and industrial self-reliance. As noted by Fu and Zhang (2011), China's case highlights the critical role of government in launching and sustaining the transition to a competitive green industry, especially through coordinated efforts to build local capabilities and leverage foreign technology.

5.4. Answering SRQ 1: China's Strategy in Developing and Maintaining Its Leadership in the Global PV Value Chain

This discussion section synthesizes the key findings and analyses from the Chinese case study, aiming to answer the first sub-research question. In summary, China has developed and sustained its leadership in the global solar PV value chain through three main strategic approaches: government orchestration in laying the foundation of a developmental state, capturing the full PV value chain, and an infrastructure-driven strategy to support PV manufacturing leadership.

5.4.1. Government orchestration in laying the foundation of a developmental state

Based on the TIS assessment, we argue that clear guidance and strong legitimacy from the central government are essential to encourage all stakeholders, such as investors, banks, industries, researchers, and universities, to participate in PV technology development. Government priorities in solar PV technology brings up the technology development through research and development activities. The decentralized implementation, where local policies were directly aligned with the central government policy encourage more entrepreneurial activities in the regions. This aligns with key factors that make it easier to do business, particularly by giving investors the confidence and protection they need to invest in PV manufacturing.

Active government orchestration plays key role in ensuring that foreign knowledge and technology can be absorbed by local capacity. Through the policies and programs release by the central government has accelerated innovation to attract investment from foreign companies. The government also increased its R&D spending and encourage more young people to pursue careers in science and research to improve their local capabilities in producing in-house knowledge and technology. Therefore, in the short-term, the technological import helped the companies started its operation while the government's policies ruled out the long-term technological and knowledge transfer to advancing domestic manufacturing capabilities.

Beyond setting long-term strategic direction, the state's role is characterized by a dynamic, real-time orchestration of both financial conditions and market demand. This orchestration is most evident in its dual-level approach to maintaining industrial momentum in China. *First*, Chinese government strategically protect its domestic firms from the global cost of capital. While interest rates were going up in many other countries, China's state-owned banks kept their lending rates below 4%. This gave Chinese solar companies a big advantage, letting them borrow money at low cost and continue investing in expanding their factories and improving technology—, ven when the global economy was unstable. This steady access to affordable financing has been a key part of the capital-heavy support system that has driven the rapid growth of China's solar industry. *Second*, the Chinese government has shown a strong ability to support its solar PV industries during difficult times to secure the market demand. When global demand dropped or foreign markets closed due to trade barriers, the government quickly responded by introducing domestic policies, like feed-in tariffs and subsidies to boost local demand. This helped keep factories running, avoided company bankruptcy, and kept the industry stable. Importantly, this approach wasn't random or one-time. It's part of a regular process where the government learns from experience, studies the results of past policies, and makes improvements over the time. For example, after facing issues like relying too much on exports or problems with certain subsidies, China adjusted its policies to better fit the situation. This ongoing policy learning, where government programs are treated like tools that can be upgraded, helps the country guide the industry more effectively and keep it strong even when global conditions change.

5.4.2. Capturing the entire PV value chain

China's rise to dominance in the solar PV value chain didn't follow a simple, step-by-step path. Instead, it was shaped by a smart and flexible strategy that focused on different parts of the value chain at different times, depending on where the biggest impact could be made.

First, China worked across all segments, but it chooses to dominating the midstream segment first which include the production of solar cells and modules. This was a smart starting point because it had lower costs and technical barriers than the upstream (polysilicon and wafers), allowing Chinese firms to quickly enter the market using imported machines. At the same time, China's low labor costs and ability to scale up fast gave it a strong early advantage. The government helped by creating a supportive business environment that encouraged private companies to join, making the market highly competitive and fast-moving.

Second, once China had gained a strong foothold in the labor-intensive industries (midstream segment), it shifted its attention to the upstream segment, which was more capital- and technology-intensive. Producing polysilicon and wafers required large investments, so the government stepped in with massive support, including low-interest loans and subsidies from state-owned banks. This support allowed China to build large, advanced production facilities, turning the country from a major importer into the world's leading producer of polysilicon. This gave China control over a key material in the global PV supply chain.

Third, after securing its position across the full production chain, from raw materials to finished modules, China moved into its next phase: leading in technology and global influence. The focus shifted from just producing at scale to becoming a leader in innovation, with huge investments in R&D and a growing number of PV patents. China also began using its foreign policy tools, especially the Belt and Road Initiative (BRI), to secure raw materials from partner countries and expand into new export markets. This global strategy has helped China lock in its leadership by controlling supply chains, shaping demand, and building a system that's hard for other countries to compete with.

5.4.3. Infrastructure-driven approach to build PV manufacturing leadership

China's success in developing its solar PV manufacturing industry is closely tied to a state-led strategy of industrial agglomeration, where both hard and soft infrastructure were built up in concentrated zones to create highly efficient production hubs. These clusters didn't grow by chance, they were carefully planned to reduce costs, boost productivity, and support long-term industrial goals.

A major foundation of these agglomerations was low-cost, government-supported hard infrastructure. One key example is affordable electricity, especially important for energy-heavy processes like polysilicon production. China kept industrial power rates low (around $0.07/kWh), mainly through its coal-based power supply. This gave domestic firms a significant cost advantage over competitors in regions with higher energy prices. In addition, the government invested heavily in transport and logistics infrastructure, placing many midstream and downstream activities in coastal provinces like Jiangsu and Zhejiang. Their closeness to major ports and dense transportation networks helped cut shipping costs and improved the flow of both raw materials and finished products, further strengthening the efficiency of these industrial clusters.

Alongside physical infrastructure, China also supported the soft infrastructure that helps industrial zones thrive. Reforms at both national and local levels improved the ease of doing business, with faster permitting, simplified registration processes, and clearer regulations attracting a large number of firms. This led to dense networks of suppliers, service providers, and competitors—key features of a successful agglomeration. At the same time, the government invested in developing human capital by expanding technical education and building research institutions near these hubs, ensuring a steady pipeline of skilled workers.

China's agglomeration strategy is also adapting to new global demands. In response to environmental concerns and market shifts, manufacturers, especially in upstream sectors like polysilicon and wafers, are expanding into inland provinces like Yunnan and Qinghai, where low-cost hydropower is abundant. This move helps lower carbon emissions and operating costs, making products more attractive in global markets that are starting to favor low-carbon goods. By building the next generation of green industrial clusters in these regions, China is positioning itself not only to remain competitive on price but also to lead in sustainability. This evolving approach shows how agglomeration, supported by targeted infrastructure and policy, remains at the heart of China's strategy for long-term leadership in the PV value chain.

6 The SADC's PV Value Chain Development

This chapter is structured in two analytical steps, detailed in the following sections. The first step involves assessing the performance of the solar PV TIS in SADC case, and the second focuses on the regionalizing PV value chain within the SADC region through the design factors and institutions analysis. The chapter concludes by addressing Sub-Research Question 2.

6.1. TIS Assessment

Table 6.1: Research Paper Analysis

Citation	Topic	Description
Baker and Sovacool (2017)	Political economy of local PV industry versus global networks (South Africa)	Examine South Africa's solar PV (and wind) sector through a political-economy lens, focusing on conflicts between building domestic technological capabilities and the pressures of global production networks. It highlights how the introduction of the Renewable Energy Independent Power Producer Program (REIPPPP) and associated local content requirements, clashed with global market forces such as rapidly declining solar hardware costs and international supply chains.
Jadhav et al. (2017)	Status and prospects of solar energy in the SADC region	Review the status of solar technology implementation in SADC. The paper compiles country-by-country information on existing projects and plans, along with policies in place, providing a baseline of efforts to incorporate solar power and replace aging fossil-fuel infrastructure as SADC moves toward a more renewable-intensive future.
Justo et al. (2022)	SADC power planning for improved access via renewables	Comprehensively review the power-system planning approaches across SADC countries aimed at expanding electricity access with renewable energy while meeting low-carbon targets. The review highlights that traditional grid extension alone has failed to eradicate rural energy poverty, prompting a shift toward decentralized off-grid solar solutions as essential for achieving universal access and sustainable energy goals in the region.
Kruger (2022)	Namibia's state utility, led solar PV auction boom	Details Namibia's rapid shift toward solar PV and other renewables through a competitive auction program, transforming from zero utility scale renewables in 2015 to over 25% of installed capacity (about 31% including small-scale projects) by 2020.
Ndlovu (2025)	Renewable transition and green hydrogen adoption in Southern Africa (MLP analysis)	Highlights the significant potential of solar PV, wind, hydropower, and green hydrogen to meet Southern Africa's energy demand while reducing reliance on fossil fuels. It examines the interactions between innovative niches and existing regimes in five countries' energy transitions, underscoring the importance of supportive policies to drive systemic change.

Source: Author's own compilation

This analysis also incorporates five peer-reviewed papers selected using the PRISMA methodology (see Figure 4.4). Compared to the extensive literature on China's PV development, publications focused on the SADC region are considerably limited. While these papers address activities related to the functions of innovation system, they differ structurally from those in the Chinese context—most notably lacking a clear timeline. Furthermore, the majority of the articles concentrate on downstream developments, reflecting the region's emphasis on energy access and electrification. As a result of these limitations, the coding process is more heavily weighted toward the downstream segment, and fewer codes were generated compared to the analysis conducted for China. Table 6.1 provides an overview of each paper included in this analysis.

Figure 6.1 presents the heat-map of the TIS assessment for the SADC case. It shows that in the downstream segment, the strongest functions are guidance of search, market formation, and resource mobilization, with no significant weaknesses relative to the other funtions performances in overall TIS assessment. The midstream and upstream segments show a similar level of performance across functions, with no standout strengths. Most functions in these segments appear in light blue on the heat-map, indicating generally quite weak performance across all functions.

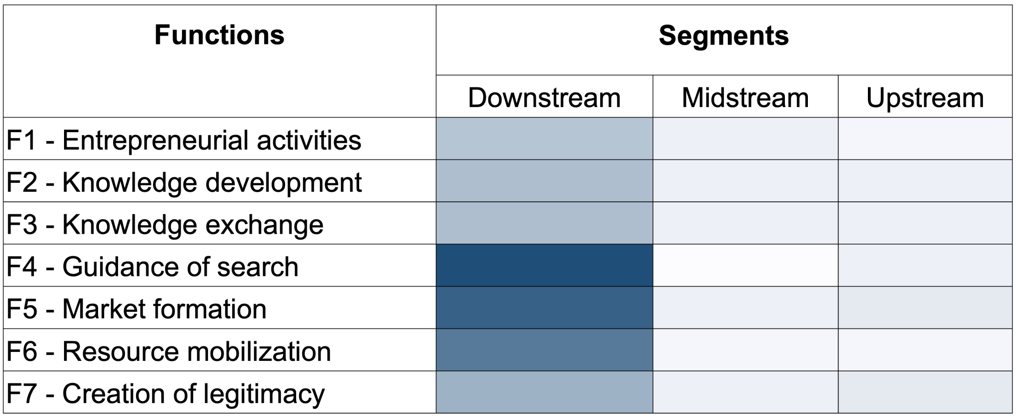

Figure 6.1: Functional Profile of the SADC's PV TIS
Note. A darker shade indicates a more strongly developed function. The heat-map in this figure is based on the calculated net values and normalized values, which are provided in Appendix 9.
Source: Author's own compilation

Moreover, by reading horizontally, we can see how each function is performed across the different segments of PV value chain. It shows that the bottlenecks mostly present in the midstream and upstream segment, relative to the downstream segment. Overall, the result indicates that the strongest developed functions are guidance of search (F4), market formation (F5) and resource mobilization (F6). Several policies, energy programs and targets set by the governments at the national or regional level, attract more investors in renewable energy sector to the countries. Some of those such as the Renewable Energy Independent Power Producers' Procurement Programme (RE IPPPP) from South Africa, energy sufficiency target through bidding program in Botswana, Renewable Energy-Based Rural Electrification (LRE-BRE) mandate in Lesotho, interconnected electrical target in the Southern African region through the he Southern African Power Pool (SAPP), and more from other countries which will be explored in the next section (Baker & Sovacool, 2017; Jadhav et al., 2017; Justo et al., 2022).

Nevertheless, those functions are considerably less developed in the midstream and upstream segments. Even in the downstream segment, we found some bottleneck though it is not significant. Some bottlenecks such as loopholes in the local content regulations that led the developers to avoid PV sector in South Africa (Baker & Sovacool, 2017).In Mozambique, the adoption of solar PV technology faces significant challenges, as many local communities cannot afford the connection fees for either grid electricity or renewable energy systems (Jadhav et al., 2017). Moreover, lack of supporting industries to solar implementation is another challenge that the region needs to tackle. There are no manufacturing industries to support the PV implementation, also with the lack of technical experts for installation and maintenance making it hard to implement the technology (Jadhav et al., 2017).

Further analysis of how each system function is performed across the segments of the value chain, along with the case in every country member will be explored in the next sub-section. An evaluation of the overall performance is also presented in the following sub-sections.

6.1.1. Overview: Actors and Institutions

An overview of the actors and institutions involved in the development of the solar PV value chain in the SADC region is presented in Figure 6.2. Policies and institutions define the rules of the game, consisting of programs, regulations, rules, and roadmap from national and regional level. For instance, power generation and regional grid rules are managed and implemented by regional electricity cooperation (SAPP). Each country also implements the local-content regulation and incentive in order to improve local production capabilities.

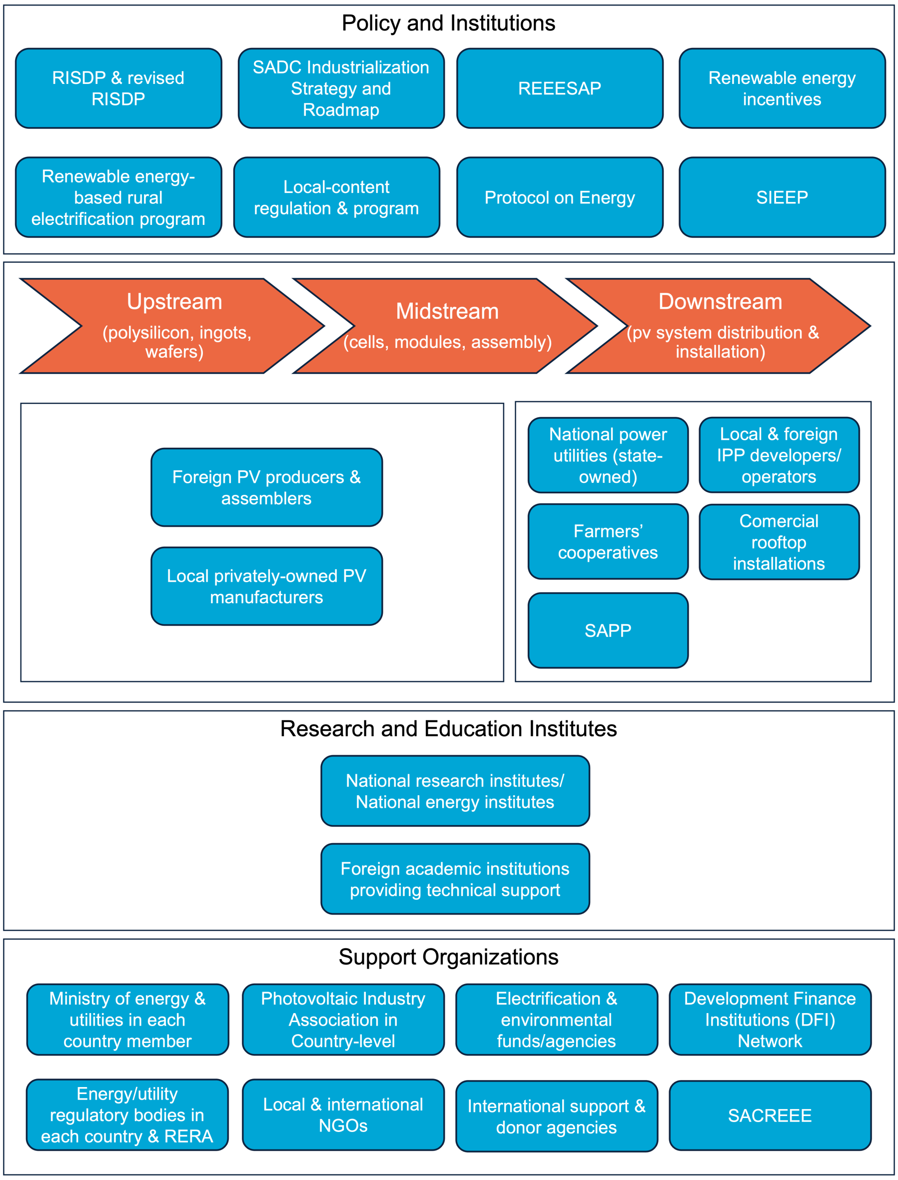

Figure 6.2: Key Actors Mapping
Source: Author's own compilation

Since its formation in 1980, energy security has been one of the main priorities for SADC, both to support daily life and to drive infrastructure projects that foster regional integration and economic growth (Jadhav et al., 2017). In 1995, SAPP was established to provide sustainable energy solutions for the region and beyond (https://www.sapp.co.zw/). The following year, SADC adopted the Protocol on Energy, creating a framework for cooperation on electricity use and development among its member states (Jadhav et al., 2017). As the global cost of solar PV technology dropped by half, the region saw steady growth in installed solar PV capacity from 2011 onwards. That same year, SADC began developing the Renewable Energy and Energy Efficiency Strategy and Action Plan (REEESAP) to

Table 6.2: Legal and Institutional Landscape in SADC

Regional Policies & Institutions	Established / Effective Year	Objectives
SADC Treaty	1992	Setting the foundation on the integration agenda in Southern Africa and creating a supportive environment for member countries to work together in various sectors.
SADC Protocol on Energy	1996	Setting the foundation for regional cooperation in sustainable energy, aligning national and regional policies, and sharing research to develop low-cost technologies.
SADC Energy Cooperation Policy and Strategy	1996	Creating effective power system management, extensive use of hydropower resources, commercialization of public utilities, and power interconnections to improve reliability and security of supply.
SADC Energy Action Plan	1997 & 2000	Aligning energy policies and regulations among member states, encouraging regional energy growth and trade, and building essential infrastructure.
SADC Regional Energy Access Strategy and Action Plan	2010	Aligning energy sector policies, laws, and regulations; planning energy infrastructure; and investing in regional interconnectors and hydropower projects.
SADC Regional Infrastructure Development Master Plan (RIDMP) and Energy Sector Plan (ESP)	2012-2027	Achieving the energy security target and access to rural needs and development.
SADC Regional Indicative Strategic Development Plan (RISDP)	2010–2020	Strengthening regional integration to speed up poverty reduction and achieve broader economic and social development goals.
SADC Regional Indicative Strategic Development Plan (RISDP)	2015–2020	Supporting regional value chains and boosting value addition in key sectors like agro-processing, mineral processing, and pharmaceuticals in the short to medium term, while expanding manufacturing capacity, competitiveness, and trade to drive long-term sustainable economic growth.
SADC Regional Indicative Strategic Development Plan (RISDP)	2020–2030	Setting out a comprehensive 10-year development agenda for addressing social, economic, political, and governance issues in the region.
SADC Industrialization Strategy and Roadmap	2015-2063	Enhancing competitiveness at the firm, industry, country, and regional levels, with the goal of raising the region's annual real GDP growth rate from 4% (since 2000) to at least 7%
Renewable Energy and Energy Efficiency Strategy and Action Plan (REEESAP)	2015	Regulating and coordinating renewable projects within the region.
SADC Industrial Energy Efficiency Programme (SIEEP)	2018	Supporting the industrialization roadmap to transform the SADC economy and build a future knowledge-based economy
SADC Industrial Energy Management Programme (SIEMP)	2015-2018	Promoting energy management in industry through delivery of training of trainers and developing manuals and materials on energy management.

Source: Author's own compilation based on SADC (2018, 2020) guide and coordinate renewable energy projects across the region. In 2016, the SADC Centre for Renewable Energy and Energy Efficiency (SACREEE) was launched as a key initiative to support regional industrialization goals and oversee REEESAP's implementation. Table 6.2 depicts several policies and institutions in the regional level that concerning renewable energy and industrialization development. Alongside these regional efforts, most SADC member states have also introduced their own renewable energy policies and strategies, which will be explored later on the next sub-chapters (SADC, 2018).

While institutions establish the regulatory and policy framework, PV value chain actors serve as the operators within this system. These actors ideally should consist upstream feedstock supplier and wafer manufacturer; midstream cell and module assembler (often located in industrial zones to meet local content regulations); and downstream players. In SADC, PV value chain actors are dominated in the downstream sector. Those actors including the state utilities and independent power producers (IPPs) who are managing large-scale solar farms, rooftop installers serving commercial and residential sectors, and farmer cooperatives or EPC firms deploying off-grid and mini-grid systems. List of PV companies were gathered through official websites providing contact of PV suppliers across the world (see https://www.enfsolar.com/ and https://www.solarfeeds.com/). We found that solar PV installers dominating the list in SADC region, following by sellers and manufacturers, with the amount of listed companies at 1438, 208, and 78, respectiveley in within the region. Table 6.3 depicts PV companies distribution in every country within SADC region.

Table 6.3: PV Companies Distribution in SADC

Country	Solar System Installers	Sellers (Distributors & Wholesalers)	Manufacturers
Angola	2	0	0
Botswana	10	0	0
Comoros	0	0	0
DRC	9	2	0
Eswatini	0	0	0
Lesotho	2	0	0
Madagascar	8	4	0
Malawi	17	0	0
Mauritius	8	2	0
Mozambique	10	0	0
Namibia	14	6	1
Seychelles	2	0	1
South Africa	1220	176	74
Tanzania	33	0	1
Zambia	29	5	1
Zimbabwe	74	13	0
Total Companies in SADC	**1438**	**208**	**78**

Note. Manufacturers actor including the companies that produce auxillary, ingots, wafers, cells, module/crystalline silicon panel, production equipment, and PV component.

Source: Author's own compilation based on data gathered from https://www.enfsolar.com/ and https://www.solarfeeds.com/

Most solar energy projects, particularly solar home systems (SHS), are funded by external donors, including multilateral development organizations, non-governmental organizations (NGOs), financial institutions, and developed countries. Between 1992 and 2017, SHS projects were implemented across various African countries with support from prominent international donors, such as the Global Environment Facility (GEF) (Adenle, 2020). The GEF funding mechanism is managed by the Implementing Agencies, including United Nations Development Programme (UNDP), World Bank Group, Specialized UN bodies like UNIDO and UNEP, and International Finance Corporation. Those agencies receive the GEF funds from the secretariat and then contract directly with in-country executing agencies such as governmental bodies, civil society organizations, private sector companies, and research institutes (see https://www.thegef.org/projects).

At the country-level, government bodies may either facilitate these initiatives by providing standards and oversight or engage directly in collaborative efforts with PV actors to meet development targets. For instance, national energy ministries that setting-up solar energy targets and rural electrification plans, and independent regulators which responsible for licensing PV projects, enforcing grid interconnection standards, and implementing local content requirements. The government of Botswana launched a competitive procurement process, inviting qualified companies to bid for a long-term contract to develop a new 100 MW solar farm (Jadhav et al., 2017). In Eswatini, collaboration between the Ministry of Natural Resources and Energy (MNRE) and the Swaziland Electricity Supply Company (SEC) (now called as Eswatini Electricity Company (EEC)), led to the implementation of several small-scale PV projects (Jadhav et al., 2017). In Namibia, the solar PV procurement process involved an intergovernmental body comprising the Ministry of Mines and Energy, the Electricity Control Board, Namibia Power Corporation, and the Namibia Energy Institute (Kruger, 2022). Moreover, the presence of Development Finance Institutions (DFI) Network, which plays a key role in financing development in the SADC region and advancing productive capacity–in line with the objectives of SADC outlined in the RISDP 2020–2030, to coordinate 41 Development Finance Institutions from 15 SADC Member States, exclude Comoros (SADC), 2023). Details of government bodies and support organizations in each country, along with their roles in PV development, are provided in Appendix .2.

6.1.2. Upstream

The upstream segment reveals significant weaknesses in the performance of the PV innovation system, with all functions show a lighter blue color relative to the downstream segment. The development of solar PV in this segment faces notable barriers, particularly in the areas of entrepreneurial activity and resource mobilization. Although countries in the region possess strong solar irradiance potential and are endowed with key minerals essential for PV production, they face challenges due to a shortage of skilled labor and a gap in substantial technological know-how (F6-h). These limitations hinder the establishment of manufacturing industries necessary to support PV implementation (F1-g), such as those producing auxiliary components, polysilicon, ingots, and wafers. Consequently, these natural resources remain underutilized.

There is also an indication that knowledge development and guidance towards this sector development are present but not strong enough to support its innovation, while there is no activities mentioned in the papers regarding the knowledge exchange activities in this segment. For instance, although various departments, donors, and private sector institutions have conducted studies on the potential of solar PV technology (F2-e) (Baker & Sovacool, 2017), most of SADC's member states have shown limited interest in establishing dedicated solar research institutes (F2-g), despite the need for specialized research to address local challenges and develop context-specific design solutions (Jadhav et al., 2017). Another example in term of guidance of search, according to Baker and Sovacool (2017), the South Africa's government approved the Special Economic Zone (SEZ) Act in 2014 in order to strengthen their current Industrial Development Zone (IDZ) Act (F4-a). However, on the other hand, the country's allocation of 600 MW per round under the Renewable Energy Independent Power Producer Procurement Programme (RE IPPPP) has been negatively received by solar PV manufacturers, who argue that this limited capacity fails to generate sufficient incentives for the growth of a domestic solar PV industry (F4-g).

Modest support is seen in the market formation (F5) and the creation of legitimacy (F7). There is an indication of emerging demand and supply in this segment, even if it's considered small. According to Jadhav et al. (2017), the national energy fund in Mozambique (FUNAE) commissioned a 5 MW per year PV manufacturing plant in 2013, including activities such as ingots & wafers production, which shows government-led stimulation program aimed at initiating market development in the upstream segment (F5-e). In addition, South Africa's SEZ Act introduces standards and criteria that manufacturing facilities must meet to qualify for financial and regulatory incentives (Baker & Sovacool, 2017). These standards contribute to legitimizing the upstream segment by establishing clear rules and reducing market uncertainty (F7-b).

6.1.3. Midstream

The midstream segment also reveals significant weaknesses in the overall system functions, with all functions show a lighter blue color relative to the downstream segment. Notably, critical functions such as 'guidance of search' and 'resource mobilization' are poorly fulfilled which potentially hinder the development of PV technology.

There is an indication that some functions are present but not strong enough to support the development of PV technology in midstream segment. Although some foreign companies entered the host country, they could left due to some other factors. For instance, some of foreign companies invest in building local PV manufacturing capabilities or service networks in South Africa (F1-c). The investments are dominated by European, US, and Chinese companies (Baker & Sovacool, 2017). However, due to very limited market size (F5-h), inadequate enforcement (F7-d) and unclear definition of local content requirements (F4-d) has resulted to some companies decided to refrain from setting up a manufacturing plant in the host country (F1-e), as Trina Solar from China cancel their investment in South Africa (Baker & Sovacool, 2017).

The involvement of foreign companies in the host country's renewable energy sector, particularly through global production networks, can significantly shape its technological and economic landscape. For example, Chinese firms have played a dominant role in the manufacturing of South Africa's PV modules and cells, influencing both the ownership of key technologies and the direction of local industrial development (F3-d) (Baker & Sovacool, 2017). Nevertheless, misalignment in the rules in local content target (F4-f), lead to the investments in low technology components instead of the high technology PV components (Baker & Sovacool, 2017), which not sustainable enough to give an optimum benefit for the local manufacturing industries to acquire technological capabilities (F3-f). PV industry association plays an important role in lobbying activity to improve the performance of PV development. According to Baker and Sovacool (2017), to stop companies from abusing local content rules by just importing solar panels and repackaging them in South Africa, the local solar industry (SAPVIA) suggested that solar modules should be assembled and laminated inside the country (F7-a). However, it was not strong enough to steer the decision making since it is under the National Treasury's authority.

Finally, unfulfilled resource mobilization and guidance of search functions, are adding more challenges to PV innovation in midstream segment. Limited skilled labour and know-how issues (F6-h) are found in the development of solar technologies, therefore deployment of PV technology is still a long way off in SADC region (Ndlovu, 2025). In addition, as mentioned before, unclear regulations (F4-d) and target misalignment (F4-g) lead to the investment cancellation and low technology investment instead of the advance ones. There is also a negative opinion (F4-g) regarding the rule of RE IPPPP set by the government that was seem as insufficient allocation to encourage the development of local downstream industry.

6.1.4. Downstream

The downstream segment is strongly developed, relative to the midstream and upstream segments. The result indicates a darker blue colour in all functions, particularly in the guidance of search (F4), market formation (F5), and resource mobilization (F6).

Strong guidance of search indicates a clear and strong policy signals and strategic vision (target) in this segment, as well as positive expectations and opinions from the expert for the development of PV technology within downstream sector. In the international level, Paris Agreement adopted in 2015 commits UN countries to intensify global efforts to limit the rise in global temperatures to below 2 degrees, required each country to prepare a National Determined Contributions (NDC) document (Justo et al., 2022; Ndlovu, 2025). According to Justo et al. (2022), in the regional level, SADC created a long-term plan called REEESAP (Renewable Energy and Energy Efficiency Strategy and Action Plan) for the horizon 2016-2030. This policy framework aims to support member countries in developing their national strategies for implementing renewable energies, energy efficiency, and action plans, in order to accelerate the energy transition in the region (F4-a; F4-c). To meet the targets, SADC etablished the Center for Renewable Energy and Energy Efficiency (SACREEE) (F2-e) to work with member countries and related institutions in the energy sector at the national level (F6-a). Consequently, every country member developed its own renewable energy policy program and targets (F6-a).

Though the regulations present, there are still some room for improvement. For example, some countries are still focusing on coal to accelerate energy access (Justo et al., 2022), while other cases are prioritizing another renewable energy option such as hydro (Ndlovu, 2025), instead of prioritizing the development and application of solar PV technology (F4-f). In other hand, lack of dependable policies and legislature directed at encouraging renewable energy (F4-e), particularly PV technology limits the investors' participation. Such case happened in DRC and Namibia (Jadhav et al., 2017).

The fulfillment of market formation function is dominated by PV project installation and market stimulation program. Figure 6.3 depicts PV installed capacity in the SADC region. Since mid-2015 under the RE IPPPP, a number of solar PV projects have become competitive in South Africa (F5-c) with new build coal-fired power plants in keeping with growing global trends which see renewable energy reaching grid parity with conventional sources of energy generation (Baker & Sovacool, 2017). In 2018, total solar PV installed capacity (F5-c) in SADC region reached 2.502,8 MW, with South Africa contributes the highest installed capacity at 2.392 MW (Renewable Energy Policy Network for the 21st Century, 2019). South Africa alone reached a total installed capacity 5.659 MWp (maximum potential power output) in 2023, with the biggest market segment from Utility scale (>50MWp), Commercial and Industrial (C&I) Large Scale and utility scale (1MWp - 50MWp), C&I-SSEG (30kWp - 1MWp), and residential (0-30 kWp) (South African Photovoltaic Industry Association, 2023). In 2019, a carbon tax was introduced in South Africa to give tax free emissions allowances (F5-e) ranging from 60–95% for modest net carbon tax rates in the range from R6-R48/tCO2 to provide emitters time to transition to cleaner operations (Ndlovu, 2025). Another example of market incentive to create more demand is through financial rebate scheme (F5-e). This scheme applied in Seychelles to built small pv arrays, allow for anybody to have a 35% financial rebate on any PV system up to 3 kW peak (kWp) (Jadhav et al., 2017).

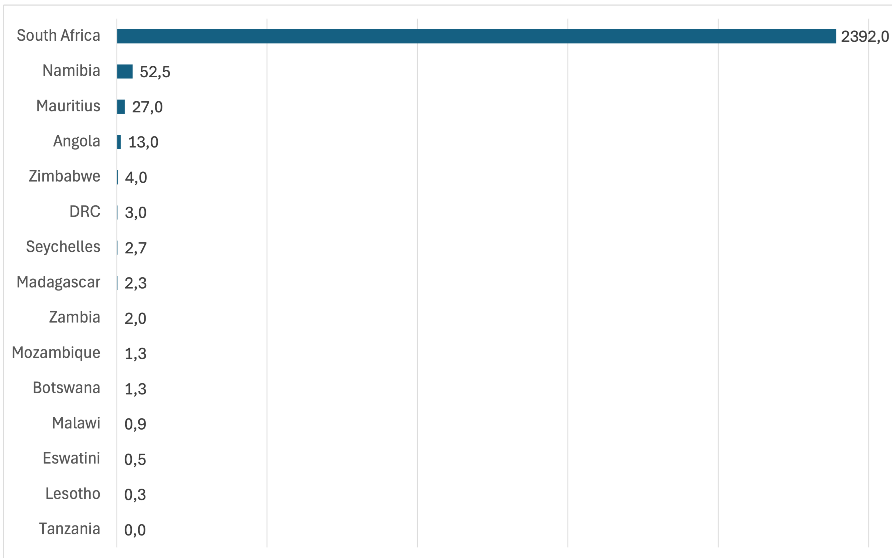

Figure 6.3: Solar PV installed capacity by country in SADC (MW), as of Mid-2018
Source: Renewable Energy Policy Network for the 21st Century (2019)

The function of resource mobilization backed up by financial source mobilization and public-private partnership activities. Most of the PV plant projects installed for public facilities such as schools, hospitals/clinics, streetlights, police stations, and solar home system for rural areas, are funded by donor programs (F6-d) (Jadhav et al., 2017). The donors spread among NGOs and foreign (Japanese) government, like in Botswana (Baker & Sovacool, 2017); World Bank's Energy Sector Management Assistance Programme (ESMAP), like in Madagaskar (Jadhav et al., 2017); and National energy funds like in Mozambique (Jadhav et al., 2017), creating more PV system market in the region (F5-a). Global financial crisis in 2018 also shift the global PV investment in the developing countries, such as SADC countries, with European, US, and Chinese companies seeking other markets to absorb their production output (Baker & Sovacool, 2017). Those companies then deployed office in the host country (F1-b).

Financial support also provided by the investment from country's government through procurement process, enables public-private partnership (F6-c). A 4.5 MW solar PV station was developed by the French company InnoSun, acting as an independent power producer (F1-b). The project spans 15 hectares and includes 30.000 installed solar panels. The total investment of US$10,79 million (F6-d) was jointly financed by InnoSun and the Development Bank of Namibia, demonstrating a co-financing model between a private investor and a national development institution (Jadhav et al., 2017). Another example in Namibia explained by Kruger (2022), where procurement process was led by NamPower (state-owned power utility) and Central Procurement Board of Namibia to select tender to build 20 MW

Omburu solar project. NamPower responsible to handle the site provision, licensing, grid connection and financing the project. Local content rules, training obligations and technology readiness requirements are also embedded in the procurement process. Meanwhile, independent power project was selected to design, build, operate, and transfer knowledge (F3-b). According to Kruger (2022),the Namibian case is probably the best regional example of the cumulative impact of a well-designed procurement program implemented in a conducive, enabling environment.

While donors scheme provided opportunity to create more demand in PV system installation, however, Jadhav et al. (2017) argue that many countries have become overly dependent on donor funding, neglecting to develop their own investment strategies at the national level. In addition, high import duties and steep lending interest rates in many SADC nations create financial barriers that discourage both foreign and domestic investment in solar technology projects.

Some other functions are presented as moderately well performed in supporting the development of downstream segment, including entrepreneurial activities, knowledge development, knowledge exchange, and creation of legitimacy. PV system installation projects in SADC countries are dominated by foreign companies and state-owned power utility (F1-b), opening more possibility to transfer knowledge from imported technology and foreign companies management style (F3-d). Moreover, limited supportive industries in the previous segments (F1-g), causes the implementation of this technology cannot be very prospective (Jadhav et al., 2017). Knowledge development is dominated by preliminary studies of the potential of building solar PV industries and feasibility studies on solar PV plant project (F2-e), involving donors and private sector institutions as well as state-owned companies. Lastly, regional institution play a key role in legitimating the development of renewable energy solution, including PV technology to the member countries, such as through SAPP, strategy and action plan, and regional summit event.

6.1.5. Overall functional profile

Across the SADC region, the performance of the solar PV innovation system shows a mixed picture. Some parts are working well, especially in getting projects built and connected to the grid, but other parts, mainly related to manufacturing and building local skills are much weaker. A brief of innovation performance in every country member are shown in the next point of analysis bellow.

Angola

With total population of 33,93 millions, only 46,89% that get access to electricity in 2020. As of October 2022, Angola's total installed power capacity was 6.019,7 MW, with renewables making up 57% of the energy mix. The most dominant energy sources are from hydropower, fossil fuels, and hybrid solar & fossil fule, respectively (https://www.sacreee.org). Moreover, in terms of manufacturing capacity, the country ranks in the lower half within SADC, with manufacturing value added (MVA) contributing only 7,7% to its total GDP (SADC, 2019a).

So far, solar PV is the main small-scale renewable energy being developed in Angola. Based on Global Solar Atlas, the country has 1.871,1 kWh/m2 per year direct normal irradiation (DNI), which considered a strong solar resources. According to the IEA, Angola does not yet have a clear national strategy for solar deployment. However, in 2005, the Ministry of Energy and Water (MINEA) announced plans for a 15-year solar PV program targeting 1,300 villages. In rural areas, where diesel fuel for generators is subsidized but often scarce, solar PV could serve as an alternative or help reduce reliance on diesel-based power (UNCTAD, 2008).

Botswana

In Botswana, 71,99% of its 2,4 milluions total population has accessed to electricity in 2020. At the end of October 2022, the country had 892 MW installed capacity and depending the 50% of its electricity demand from import. Based on Global Solar Atlas, the DNI value for Botswana is 2.411 kWh/m2 per year, which higher compare to Angola.

Despite the high potential of its solar irradiance, solar PV contributes only to 7% of installed capacity in Botswana (https://www.sacreee.org). According to Jadhav et al. (2017), although Botswana has not yet built a large-scale solar PV plant, NGOs have supported the installation of solar PV systems in many rural schools, beginning in 1986 with 19 primary schools in the first phase. In urban areas, solar technologies are more common at the household level, such as solar water heaters and privately owned PV systems.

The dissemination of PV technology in the country faces another challenge in the production sector. According to SADC (2019a), Botswana's manufacturing sector is considered left behind compare to other countries in SADC, with constributes only 5,2% of total GDP in 2019, indicating the lack of production capacities and making it hard to catch up with development of PV technologies.

Comoros
Comoros has a decentralized installed capacity of 46 MW, mainly dependent on biomass and imported heavy fuels. Solar PV offers a potential, with a DNI score of 1.525,7 kWh/m2 per year, according to the Global Solar Atlas. The country, with a population of about 0.89 million, had 86.7% electricity access in 2020 (https://www.sacreee.org). However, its MVA accounts for only 6,8% of country's GDP, reflecting limited industrial capacity (SADC, 2019a).

Despite the solar potential, renewable energy use remains limited in the country, with only 6 MW comes from solar resource. A Power Sector Master Plan has been prepared to raise renewables from 16% to 30% by 2033, but a detailed least-cost power development plan is still missing to guide generation, transmission, distribution, and financing (WorldBank, 2022). The Government of Comoros has recently invited developers to design, build, and operate several solar projects with storage, aiming to strengthen the country's solar PV's supply (Skujins, 2023).

DRC
According to SACREEE, the Democratic Republic of Congo (DRC) had a population of about 92,38 million, but only 19,1% had access to electricity in 2020. The country's total installed capacity stands at 2,819 MW, largely generated from hydropower (https://www.sacreee.org. Compared to other SADC countries, its solar potential is relatively modest, with a DNI of 1015,1 kWh/m2 per year. As noted by Jadhav et al. (2017), the only existing solar capacity consists of small pilot systems installed by private companies and NGOs, totaling just 83 kW across 836 installations. On the other hand, the DRC shows relatively strong industrial capacity within the region, with MVA contributing 14% of total GDP (SADC, 2019a).

Eswatini
Eswatini has an installed capacity of 71 MW which is owned and operated by the Eswatini Electricity Commission (EEC), the national utility. By 2020, about 79,7% of its 1,17 million people had access to electricity. The Global Solar Atlas records the country's DNI at 1.649,1 kWh/m2 per year, which consider as moderate. Currently, a 13,75 MW solar PV plant contributes around 10 MW of guaranteed capacity to the national grid (https://www.sacreee.org).

Eswatini has been using solar technology for over a decade, mainly for lighting application. More than 700 households have received 40Wp Solar Home Systems (SHS), often through credit-based schemes for clients. Most of these projects were funded by non-governmental organizations, while schools and public institutions across the country have also benefited from solar installations (Westra et al., 2001). According to IRENA (2014), the Ministry of Natural Resources and Energy (MNRE), together with the Eswatini Electricity Supply Company (EEC), has carried out several small-scale solar PV projects. These include 25 kW system in the village of Bulembu, 32 kW installation at the Mbabane hospital blood bank, 60 kW system at the University of Swaziland's Luyengo campus (now University of Eswatini), and a 32 kW system at the Mhlumeni border post. Notably, Eswatini also stands out in the region for its industrial base, with MVA contributing 29% of its GDP, the highest share among SADC member states (SADC, 2019a).

Lesotho
In October 2022, Lesotho had an installed capacity of 74 MW, of which 70 MW came from hydropower. By 2020, approximately 77,73% of its 2,16 millions people had access to electricity, though only 34,93% of rural residents were connected (https://www.sacreee.org. The country has strong solar potential, with a DNI of 2.606,9 kWh/m² per year, yet solar PV remains far less developed compared to hydropower. On the economic side, manufacturing contributes significantly to Lesotho's economy, accounting for 16% of GDP (SADC, 2019a). Manufacturing also dominates membership in the country's main business association, the Private Sector Foundation of Lesotho (PSFL) (SADC, 2021c). These progress suggest a potential foundation for developing a solar PV industrial ecosystem.

On the other hand, Taele et al. (2011) argue that expanding electricity access in rural areas remains a serious challenge. To address this, the government created the Rural Electrification Unit (REU) within the Department of Energy (DOE) to promote rural electrification and encourage PV adoption by offering subsidies to make it a viable business opportunity. However, the REU faces limited capacity, and local government structures are not yet prepared to take on the role of electricity distributors.

Madagascar
Among 28,43 millions population, only 33,74% got electricity access in 2020. Malawi has an installed capacity of 246 MW, with hydropower providing about 68% of the country's electricity, while the rest comes from diesel plants, solar PV, and biomass waste (bagasse) (https://www.sacreee.org. Meanwhile, solar PV has a high potential with the country's DNI score at 2.395 kWh/m2 per year. Its manufacturing sector also contributes just 9,1% to the country's GDP, indicating moderate industrial capacity compared to other countries in SADC (SADC, 2019a).

According to Jadhav et al. (2017), Madagascar's solar initiatives have so far been limited to small, community-based projects, such as a 75 kW off-grid solar plant serving two villages and a 3,2 kW solar micro-grid installed by a private company. However, the country is working on a national solar map with support from the World Bank's Energy Sector Management Assistance Programme (ESMAP) and has submitted an Expression of Interest under the SREP, identifying solar energy expansion as one of its key priorities.

Malawi
By 2020, only 14,87% of Malawi's population (19,65 millions) that had access to electricity, highlighting as the lowest rates of household electrification in the world (Jagger et al., 2022). The country has an installed capacity of 583 MW and operating capacity 240 MW, which dominated by around 98% hydro power from the Shire River and heavy fuel oils (https://www.sacreee.org).

According to the Global Solar Atlas, Malawi has a quite high solar potential with a DNI of 1856,9 kWh/m2 per year. One of the most significant steps in Malawi's use of solar PV was the commissioning of an 850 kW grid-connected system at Kamuzu International Airport in Lilongwe in September 2013 (Zalengera et al., 2014). Additionally, Zalengera et al. (2014) also found that Malawi's National Energy Policy provides clear steps to improve the country's energy sector, but progress is held back by several challenges. These include limited financing for large-scale projects, a shortage of skilled workers, weak coordination among local institutions, unclear regulations, and issues linked to political governance. Another challenge lies in the production sector, where manufacturing only contributes as much as 9,1% of its GDP in 2019, same as Madagascar (SADC, 2019a). SADC (2021c) notes that Malawi has placed strong emphasis on industrialization as a driver of economic growth by prioritizing several key industries. However, solar PV has not been included among these priority sectors.

Mauritius
Access to electricity in Mauritius is almost 100%, with total population 1,27 millions people. The country has 848 MW installed capacity, which the 46% supplied from thermal power stations and hydroelectric plants (https://www.sacreee.org. Its solar irradiance is recorded in 1332 kWh/m2 per year, which is not too significant compare to other SADC's member states.

In Mauritius, according to Palanichamy et al. (2004), private sector involvement in the energy sector is quite significant. In 1998, the government launched a pilot project by installing 125 PV systems for street lighting and government buildings to promote renewable energy development, with the sector projected to grow by about USD 1 million annually. However, Palanichamy et al. (2004) also found that the development of PV sector in Mauritius faces some challenges. The country's small land size limits the potential for large-scale solar plants, making efficiency harder to achieve. In addition, there is a lack of adequate equipment and training for PV installation, maintenance, and repair. The manufacturing sector makes only a moderate contribution to GDP relative to other SADC members, at 10.9% (SADC, 2019a). According to SADC (2021c), industrialization agenda in Mauritius is still guided by the old Industrial and SME Strategic Plan (2010-2013), without clear priority sectors. While this lack of direction poses challenges, it could also provide an opportunity to position solar PV as a priority industry.

Mozambique
Among 32,16 millions population, only 30,6% that had access to electricity in 2020. Mozambique has 2.796 MW installed capacity which is primarily generated by the government-owned the Cahora Bassa

hydro dam and operated Hidroeléctrica de Cahora Bassa (HCB) (https://www.sacreee.org. For off-grid electrification, the main actor is FUNAE (National Fund for Rural Electrification), a public institution created in 1997 with strong donor support. Donors have been heavily involved in the country's energy sector reforms, offering financial, legal, and organizational assistance (Ahlborg & Hammar, 2012).

Based on the Global Solar Atlas, Mozambique has a DNI of 1603,9 kWh/m2 per year, which relatively higher that one in Comoros. Ahlborg and Hammar (2012) argue that even when solar PV is being promoted by FUNAE, the REA, and international donors; the adoption of this technology still faces challenges. It is often considered expensive and unsuitable for productive use because of its low capacity. In Mozambique, political priorities are the main drivers for renewable energy development, where subsidies and pro-poor policies have been used to increase electricity access in rural communities. Moreover, same as Madagascar and Malawi, its manufacturing only moderately contribute to the GDP at 9,1%, which left a room for improvement in the production sector (SADC, 2019a).

Namibia
Namibia has a total installed capacity of 644 MW, mainly supplied by four NamPower owned plants: Anixas (22 MW, diesel), Paratus (16 MW, diesel), Van Eck (120 MW, coal), and Ruacana (330 MW, hydro). This capacity is complemented by around 170 MW of solar PV generated from 22 sites across the country. However, about 60% of Namibia's electricity needs are still met through imports from South Africa's Eskom and the Southern Africa Power Pool. From those energy sources, only 56,26% of its 2,59 population had electrified by 2020 (https://www.sacreee.org).

Namibia has a very strong solar irradiance with a DNI of 2.898,7 kWh/m2 per year. According to Ruppel and Althusmann (2016), one of the main uses of solar PV in Namibia is for water pumping systems (PVP), especially on cattle farms. The number of both on-grid and off-grid PV plants is growing in Namibia. A key example is the 1,1 MW rooftop PV system at National Breweries, which now supplies about 34% of its electricity needs and shows how dependence on the main grid can be reduced. NamPower has also installed a 640 kW grid-connected system, highlighting local expertise in solar PV. However, there is still no law that allows private owners (IPPs) to sell excess electricity back to the grid. The lack of such policy limits investor's participation .

On the manufacturing side, Namibia has 11,7% shares of its MVA to country's GDP, which relatively moderate compared to other SADC member states (SADC, 2019a). Namibia industrialization strategy is putting the private sector as a lead player, while foreign investment is expected to be the main catalyst for the development. Also, putting education and training as key priorities (SADC, 2021c). However, in the priority areas, the country doesn't mention any PV technologies on the industrialization strategy.

Seychelles
With only 0,1 million population, everyone in Seychelles had an access to electricity by 2020. Seychelles has an installed power capacity of 119 MW, which is almost entirely dependent on imported fossil fuels, with renewables accounting for only about 5% of the energy mix (https://www.sacreee.org). It relatively has lower DNI compared to other SADC countries, with 1.246,2 kWh/m2 per year.

The Seychelles Energy Policy 2010–2030 focuses on sustainable energy development by promoting efficiency, renewable energy, and reducing oil dependence to strengthen energy security (Jadhav et al., 2017). Progress in solar adoption has been slow, but the government has introduced a Financial Rebate Scheme to encourage private companies and households to install small PV systems. The scheme offers a 35% rebate on systems up to 3 kW peak (kWp), with varying subsidies for domestic and commercial users depending on system size. This initiative is designed to boost solar uptake and expand the country's installed PV capacity.

South Africa
In South Africa, 84,39% of its 60,04 millions people had access to electricity by 2020.The country's total installed capacity reached 48,521 MW, with 32,246 MW in operation. Power is supplied by the national utility Eskom along with independent power producers (IPPs). Among the IPPs, solar PV contributes 2,287 MW, making up only 4% of total generation (https://www.sacreee.org). The NDI in South Africa counted for 2.687,8 kWh/m2 per year, which considered as second highest solar irradiance in SADC.

According to Jadhav et al. (2017), South Africa is one of leading countries in Africa for renewable energy development. The government has created a supportive market for independent power producers

(IPPs) by introducing policies and incentives such as feed-in tariffs and power purchase agreements. These factors make investment in renewables more attractive.

In the production side, the country has 11,8% share of MVA to its total GDP in 2019 (SADC, 2019a). In 2007, the government approved a National Industrial Policy Framework (NIPF), to facilitating sector diversification. This policy framework structured thirteen strategic programmes, including innovation and technology, and regional and African Industrial and Trade Framework. There are several agencies that being established, such as Council for Scientific and Industrial Research (CSIR) as research and statistic agencies, Technology Innovation Agency (TIA) as key partner institutions in the implementation of the Industrial Policy Action Plan (IPAP), National Empowerment Fund (NEF) as finance and business development institutions, and many more institutions (SADC, 2021c).

Tanzania
Tanzania has 1.695 MW installed capacity and operating capacity of 1.529 MW. Solar only contributes to 1% of the country's electricity generation mix. Tanzania also still importing from Uganda and Zambia to meet local electricity demand. A number of IPPs contribute to 253,32 MW, where only 46,1 MW is generated from hydro, solar, biomass and wind. By 2020, 39,9% of its 61,5 millions population had access to electricity (https://www.sacreee.org).

With a DNI of 2053,5 kWh/m2 per year, according to Hansen et al. (2015), Tanzania began using solar PV in the 1970s to electrify rural institutions such as schools, churches, and health centers through government-funded projects. Since then, the PV market has largely relied on government procurement and donor-supported programs for these institutions. A consumer market for PV only started to grow in the late 1990s and early 2000s, mainly influenced by the expansion of Kenya's solar PV industry into Tanzania.

Its manufacturing sector only contributes to 8,5% GDP (SADC, 2019a). To attract more private investment in the manufacturing sector, Tanzanian governments provide some financial incentives schemes. For instance, value added tax (VAT) incentives on project capital goods such as plant; 0% import duties on project capital goods and raw materials; 10% import duties for semi-processed goods; and 50% allowance for wear and tear of plant machinery in year one. To access those kind of incentives, local companies fully owned by Tanzanian citizens must invest at least USD 100.000. In contrast, foreign investors, whether operating independently or through joint ventures, are required to commit a minimum of USD 500,000 (ACE-TAF, 2021).

Zambia
Zambia has an installed capacity of 3,493 MW and an operating capacity of 3,450 MW, with solar PV contributing just 3% of the energy mix. Although the country is a net exporter of electricity and aims to add 2,015 MW of solar capacity by 2030, only 44.5% of its 18.9 million people had access to electricity in 2020 (https://www.sacreee.org/index.php/fr/node/61).

The country has a NDI of 2127,2 kWh/m2 per year, which considered a high potential for solar PV installation. The Zambia PV Energy Service Company (ESCO) project began in June 1998, led by the Department of Energy (DoE) of the Government of Zambia. It was financially supported by the Swedish International Development Authority (Sida) and advised by the Stockholm Environment Institute (SEI). As a pilot initiative, its goal was to test whether the PV ESCO model could work effectively and be integrated into Zambia's rural electrification strategy. Since 2000, a hundred SHS has been operated by the ESCO in the town of Nyimba, Zambia (Gustavsson & Ellegård, 2004).

Zambia's manufacturing sector contributes only 7,6% to the national GDP, a relatively low share compared to other SADC member states (SADC, 2019a). To drive manufacturing industries in general, the government governments provide 2-7% discount on income for the first year of listing on the Lusaka stock exchange (Zambia's designated agency for issuing International Securities Identification Numbers–ISIN). Moreover, the governments also offer a duty free importation of most capital good. However, only projects with investments above USD 500.000, located in industrial parks, priority sectors, or rural enterprises, qualify for fiscal incentives (ACE-TAF, 2021). Zambia's National Industrial Policy aims to shift the country from mainly producing and exporting raw materials to becoming a net exporter of value-added goods. Both mineral and energy sector are becoming ones of the focuses of this policy (SADC, 2021c).

Zimbabwe
In 2020, about 52.8% of Zimbabwe's 15.09 million people had access to electricity. The country has an installed capacity of 2.771 MW, with 1.795 MW in operation. There is increasing contribution from IPPs who collectively produce 131 MW from 3 bagasse projects (74%) and 8 mini hydro projects (24%). However, solar PV contributes only 2% of this despite Zimbabwe's high solar potential, with a DNI of 2.261,2 kWh/m² per year (https://www.sacreee.org).

Between 1960 and 2007, Zimbabwe emerged as one of the early leaders in solar PV adoption, with the industry becoming active in the 1960s and expanding rapidly during the 1970s (Bawakyillenuo, 2012). A major driver of this growth was donor support, especially in the 1990s, when Zimbabwe benefited from large-scale PV programs funded by UNDP-GEF and JICA. The Rural Electrification Programme and the gradual extension of the national grid also shaped the widespread uptake of PV in rural households. Supportive policy measures, such as tax and import duty exemptions on PV components in the 1990s, further boosted adoption. For instance, during the GEF/UNDP project (1993–1998), all imported PV components were exempt from duties. Moreover, the revolving fund managed by the Agricultural Finance Corporation (AFC), which offered low-interest loans to prospective PV users, played a key role in sustaining the momentum of PV dissemination in the country.

In the production stage, manufacturings sector in general contributes to the 11,9% of its country's GDP, which considerably moderate compare to other SADC country members (SADC, 2019a). SADC (2021c) notes that 60% of the key business association in Zimbabwe (Confederation of Zimbabwe Industries-CFI)is dominating by manufacturing sector.

Finally, to conclude the overall PV TIS performance in SADC region, the next points will explore the factors considered as drivers and barriers toward the development of PV technology in the region. Overall, the system functions in SADC perform moderately-well. The strongest areas are considerably in four functions, including:

1. Policy direction (F4)
   Governments across the region, backed by international agreements like the Paris Agreement and regional plans like REEESAP, have set clear goals and long-term signals that give investors confidence—especially for building new solar power projects. Though there are still missing points on the current regulations, such as no clear directions towards the PV sector development. However, the presence of renewable energy and manufacturing guidance in the region and in some of the countries, indicating a good starting point to push the development of PV technology in the manufacturing sector.
2. Market formation (F5)
   Countries like South Africa and Namibia have run successful solar auctions, and other places have introduced rebates and carbon pricing. As a result, installed solar capacity has grown from almost nothing to several gigawatts in just a decade.
3. Resource mobilisation (F6)
   There's also solid support in this function, especially for solar projects. Multilateral banks, donors, and private investors are regularly funding solar mini-grids, public building installations, and large-scale solar farms. Programs like Namibia's Omburu solar project combine land, grid access, and affordable financing to make investment easier.
4. Creation of legitimacy (F7)
   Public and political support for PV installation is also strong. Regional groups like SACREEE and SAPVIA promote solar effectively, legal standards help reduce investor risk, and the technology enjoys strong public support.

Nevertheless, the system struggles in three key areas, the knowledge- and skills-based functions that lag behind.

1. Entrepreneurial activity (F1) This function actively present for solar developers and installers, but very weak in manufacturing. There's a shortage of skilled workers and technical knowledge, making local production of solar components rare and risky.
2. Knowledge development (F2) Most research is short-term and focused on feasibility studies. There are very few dedicated solar PV R&D centers, and universities are rarely involved or ref-

erenced in solar PV development activities, suggesting missed opportunities to leverage local academic capacity.

3. Knowledge exchange (F3) Foreign companies may bring basic operational know-how due to low-tech investment preference, but weak local supply chains and few partnerships mean little long-term learning happens, especially in high-tech areas.

Overall, while the strongly-developed functions are leaving a room for improvement in some of the activities, and therefore also for other functions performed moderately. Most importantly, weaknesses in the unfulfilled functions within the midstream and upstream segments that require extra attention for every actors and intitutions to better develop the PV manufacturing sector in SADC region.

6.2. Regionalizing PV Value Chain in SADC Region

6.2.1. Designing PV Value Chain

This section brings together the findings on each country's innovation performance from the previous analysis and examines the design factors that support PV manufacturing development in each SADC member state. By identifying these design factors, it highlights the areas where each country has competitive strengths that can contribute to building a regional PV value chain.

The analysis will be structured using the design factor criteria from Macé et al. (2023), with some modifications. Previous findings show that the manufacturing segment of the PV value chain in SADC is still very limited, with only 78 manufacturers out of a total of 1,724 PV companies (4.4%). Moreover, the sector is heavily concentrated in South Africa, which accounts for 74 of these manufacturers. This indicates that PV manufacturing in SADC remains at an emerging stage.

According to Bamber et al. (2014), key factors that affecting competitiveness of manufacturing in GVCs, particularly for developing country context where manufacturing capacities are considerably low, including human capital, standard & certification, national system of innovation, infrastructure, and trade & investment policy & facilitation. Human capital, including labor cost & the availability of skilled workers, which also defined by Macé et al. (2023) as the key requirement for OPEX and competence-intensive industries. Standard and certification is aimed for some manufacturing chains that require strict adherence such as medical device and aerospace, therefore this factor is going to be ignored in this research. National system of innovation is indeed part of the TIS assessment, therefore it was concluded in the previous chapter.

Moreover, infrastructure including energy, water, and transportation are indeed part of the baseline factor from Macé et al. (2023). Lastly, investment policy will mainly focusing on the bureaucracy and procedural in doing business, therefore it will be alight with the ease of doing business and access to capital. Therefore, this subsection will explore the design factors in developing PV manufacturing in SADC using these criteria: existing industrial ecosystem, existing of upstream PV actors, infrastructure readiness, availability of raw material, ease of doing business, access to capital, and labor cost & availability.

This analysis will be limited on the available of published information. Therefore, it might not cover all country members in SADC in every stage of analysis.

Industrial Ecosystem and Infrastructure Readiness

Special economic zone (SEZ) will be used to guide the functioning of manufacturing ecosystem in the region. In China, solar PV manufacturing capacity is concentrated in a few provinces and autonomous regions, which are areas granted a certain level of self-governance by the central government, which close to the concept of SEZ or agglomeration. Therefore information about the performance of SEZs, along with the infrastructure readiness in SADC member states will be explored here.

Sount Africa, first of all, shows a succeed strategy in managing the SEZs, where those are created to exploit the transportation nodes. The country has 15 SEZs, including the actual and potential ones. At first, the location distribution for its SEZs appeared to be mainly in coastal provinces due to export-focus reason. Then, after the policy reforms, there is an increase in the number of applications for different provinces. There is an alignment between the SEZs' location and the transportation facilities. For instance, Coega SEZ is adjoined to the Port of Ngqura, which serving as a gateway to global market.

There is also one in Port of Saldanha in which closes to the global southern trade round, and Dube Trade Port that positioned between the two biggest sea ports in Southern Africa and linked to the rest of Africa by road and rail (Dube et al., 2020).

Mauritius also choose locations based on the closeness to the transport facilities. With a total land area of 2,040 km², it has 19 SEZs. Those are formed as EPZs, with mainly singer-factory units and freeport zones.The freeport zone initiative has strategically ensured that all the zones are in proximity of either air or sea transport routes to facilitate international trade. This enhances the chances of success. The government also create a clear programme based on the legislation to confirm that there is an institution responsible for ensuring that both hard and soft infrastructure are in place. This is expected to go a long way in attracting investors into the zones (Dube et al., 2020).

In **Zimbabwe**, SEZs are differentiate into two categories, a single sector and multi-sector. It lies on the variety of the industrial sector or the produced goods within the SEZ. The country has 17 SEZs from public-and private-owned companies, and those have been declared at geographic locations where there are no discernible advantages in terms of market access and transportation nodes, hence those are not easily accessible. However, the six geographic areas that have been designated as public SEZs have mainly targeted urban areas with road and railway networks, although the state of the infrastructure is still a problem.

The SEZs in **Namibia** mainly exist in the form of Export Processing Zones (EPZs). This EPZs targeting export-oriented bussiness. Therefore, most of the SEZs' location targeted border towns and ports. However, due to the constant breakdown of railway infrastructure and it cannot handle enough cargo, some EPZ companies are forced to use other, more expensive transport options (Dube et al., 2020). In **Tanzania**, the zones are formed as both SEZs and EPZs, where owned by government and private sector. According to Dube et al. (2020), the development of the EPZ and SEZ programmes in Tanzania was not informed by any evidance based research to determine the competitiveness and strategic positioning of the programmes. Therefore, that makes it possible for most of the SEZ projects to lack the basic infrastructure required to attract investors.

The establishment of SEZs in **Zambia** has involved collaboration between the government, private sector, and foreign partners. The Multi-Facility Economic Zones (MFEZs) initiative was first introduced in 2005 through support from the Japan International Cooperation Agency. The Lusaka East MFEZ, declared in 2007, became the country's first zone and is better known as the Zambia–China Economic & Trade Cooperation Zone (ZCCZ)—notably the first Chinese overseas economic and trade cooperation zone in Africa. However, as noted by Dube et al. (2020), these zones face major infrastructure challenges, including unreliable water supply, electricity shortages, poor sewerage, weak transport logistics, and inadequate road networks. Such deficiencies discourage investment, as illustrated by the Lusaka East MFEZ, which has had to reject several investors due to severe power shortages. The current MFEZ framework does not require adequate infrastructure to be in place before licensing investors, which undermines the overall success of the zones.

The rest of the country members, according to UNCTAD (2019), have no or few zones and are planning to set up at least one new SEZ. Those country including Angola (1), Eswatini (2), Mozambique (2), and DRC (4). Relative to the GVC participations, **Botswana**, with its 8 SEZs was performed very well in the GVC participation. While, in term of FDI attraction and trade growth, Angola and Eswatini are placed in the bottom five economies, inline with their less available SEZs. Other country like Seychelles, Comoros, Lesotho, and Malawi cannot be identified due to the availability of published information.

Transport Infrastructure Readiness

By 2001, according to SADC (2021b), only about half of SADC's paved roads were in good condition, with higher standards in Botswana, Lesotho, Namibia, South Africa, and Zimbabwe, while countries like Zambia, Mozambique, and Angola lagged behind. Unpaved roads were in even worse shape, with less than 40% considered good. Although rehabilitation efforts, such as in Mozambique, have brought improvements, many member states continue to face high maintenance costs, poor management, and limited funding, leading to deteriorating road networks and rising transport costs across the region.

In the mainland area, SADC has the road corridor (SADC corridor) and railway corridor (SARA corridor). To connect it with the main port, the list of ports are shown in Table 6.4. In Mauritius, despite the worked

Table 6.4: SADC Regional Main Ports

Regional Port	Country	SADC Corridor	SARA Corridor	World Port Source Category
Dar-es-Salaam	Tanzania	Central, Dar-es-Salaam	Central, TAZARA	Large seaport
Zanzibar	Tanzania	none	none	Small harbour
Mtwara	Tanzania	Mtwara	none	Small pier, jetty or whard
Mahe/Port of Victoria	Seychelles	none	none	Small seaport
Port Louis	Mauritius	none	none	Medium seaport
Tamatave/Toamasina	Madagascar	none	none	Medium seaport
Nacala	Mozambique	Nacala	Nacala	Small seaport
Beira	Mozambique	Beira	Beira	Medium seaport
Maputo	Mozambique	Maputo, Limpopo	Limpopo, Ressano Garcia, Goba	Medium seaport
Richards Bay	South Africa	none	Richards Bay	Medium seaport
Durban	South Africa	North-South, Maseru-Durban	Plumtree, Beitbridge	Large seaport
Port Elizabeth	South Africa	none	none	Medium seaport
Cape Town	South Africa	Trans-Orange	none	Medium seaport
Luderitz	Namibia	Trans-Orange	none	Small harbour
Walvis Bay	Namibia	Trans-Caprivi, Trans-Cunene, Trans-Kalahari, Trans-Orange	Namibian	Small seaport
Namibe	Angola	Namibe	none	Small harbour
Lobito	Angola	Lobito	none	Medium deepwater seaport
Luanda	Angola	Malange	none	Medium deepwater seaport
Matadi/Boma	DRC	Bas Congo	none	Small river port

Source: SADC (2021b)

strategy in putting the SEZs close to the sea transport routes to facilitate international trade. However, because it is a small island, including Seychelles, so naturally the ports don't appear in SADC land transport corridors.

Some challenges appears in the port sector. The port network in the region faces several challenges that limit efficiency and capacity. Poor coordination between transport modes such as road, rail, and port operations often causes congestion, while inadequate materials handling infrastructure further slows processes. Customs and trade delays, sometimes lasting up to two months, disrupt logistics chains and increase costs. Many ports also suffer from poor location and layout, being surrounded by dense urban or industrial areas that leave little room for expansion. Access roads are frequently congested, and railway connections are outdated, inherited from older systems. Additionally, insufficient berths and limited draft capacity restrict port operations, especially as demand often matches or exceeds existing capacity (SADC, 2021b).

Energy Supply for Industrialization

According to the data from SAPP, there are some excess and shortfall in the electricity supply from the utility members. The installed capacity in the region is still dominated by coal-fired plants, mainly in South Africa. As of October 2017, only **South Africa**, **Angola**, **Mozambique**, and **Zambia** that has excess production capacity of 3.731 MW, 350 MW, 232 MW, and 211 MW, respectively. In total, SAPP produced an excess generation capacity of 2.957 MW by the end of 2017. The surplus electricity generation is predicted to continue in the future as SAPP will commission an average of 5.000 MW per year in the next six years (SADC, 2018). To see the capability of every country in providing electricity access and the share of industry in energy consumption, Table 6.5 is provided.

While most of SADC member countries are still struggling due to less than a half electricity access rate

Table 6.5: Energy Consumption in SADC

Country	Electricity Access Rate (%)	Share of Industry in Energy Consumption (%)
Angola	32	8
Botswana	56	18
DRC	14	16
Eswatini	65	52
Lesotho	28	36
Madagascar	17	19
Malawi	12	26
Mauritius	100	26
Mozambique	21	20
Namibia	50	12
Seychelles	100	28
South Africa	86	39
Tanzania	16	15
Zambia	28	32
Zimbabwe	40	8

Source: SADC (2018)

in their population. Those could be a reason in the demand side, where the country needs to provide more affordable electricity access; but also could be a challenge for the industrialization where not enough electricity for production activity. Meanwhile, **Eswatini** marked as a country with the highest share of industry in energy consumption, but also provided more than half of the electricity access. This can be a sign of strong industrial capacity and readiness for further manufacturing.

On the other hand, there are interesting points where country like **Angola** who has excess electricity production capacity, but share a very small electricity access and industrial consumption. This can be a sign that even if the power plants produce enough, yet it cannot reach the demand location due to bottlenects in the infrastructure and grid. Moreover, it could also be meant that the industrialization remains underdeveloped. In PV manufacturing, electricity provides 80% of the total energy used. The majority of energy is consumed by production of polysilicon, ingots and wafers (upstrem segment), because they require heat at high and precise temperatures (IEA, 2022). Therefore, to build more manufacturing capabilities, particularly in upstream segment, abundance electricity generation is needed.

Existing Upstream Ecosystem and Mineral Availability

Among thousands PV companies that opererate in SADC, none of those produce either auxillary, ingots, or wafers (lies under upstream segment). Detail of the companies their production activities can be seen in Appendix .2. This information is gathered from two websites that provide PV suppliers list from across the world (see https://www.enfsolar.com/ and https://www.solarfeeds.com/). It can be a sign that building solar PV manufacturing, particularly in the upstream segment could be extra challenging in the region since there is no incumbent industries that can be a successful proof of this sector (Macé et al., 2023).

However, the abundance minerals and the presence of mineral extraction companies provide another possibilities for SADC. As mentioned in chapter 2, there are few of minerals needed for PV production that are available in SADC, such as Copper and Tin in the DRC and Zambia. Cloete et al. (2023) listed the core minerals for the African green mineral strategy, particularly those needed for solar PV production, including Aluminium, Copper for wiring/cable, Iron-Steel, Nickel for battery, and Zinc for anticorrosion material. Table 6.6 is the list of major companies in SADC that produce particular minerals needed for PV manufacturing.

From those lists, we can see that many mining companies in Zambia are dominating by the local players. Meanwhile, in DRC most of the companies are from China, which could be meant as the presence of a strong relation between China and DRC. The presence of major mining companies in the region could be a high potential for PV upstream sector development, since there is a major material for this production process. However, since those companies mainly just extracting raw resources, therefore developing or mainstreaming refining industries are mandatory.

Table 6.6: Major Mining Companies in SADC

Country	Companies	Parent Country	Mineral
Botswana	Sandfire Resources	Australia	Copper
	Premium Nickel Resources Ltd	Canada	Nickel, Copper
	Global Natural Resources Investments (NGRI)	Botswana	Copper
DRC	Générale des Carriès et des Mines, Gécamines	DRC	Copper, Cobalt
	Entreprise Générale du Cobalt's (EGC)	DRC	Cobalt
	Glencore	Switzerland	Copper, Cobalt
	CMOC	China	Copper, Cobalt
	MMG Ltd	Australia/Hongkong/China	Copper
	Ivanhoe	Canada	Copper, Zinc
	Eurasian Resource Group (ERG)	Luxemburg/Kazakhtan	Copper, Cobalt
	China Railway Engineering Company (CREC)	China	Copper
	Jinchuan Group	China	Copper, Cobalt
	Zhejiang Huayo Cobalt	China	Copper, Cobalt
	China Non-Ferrous Metal Mining Group (CNMC)	China	Copper
	Zijin Mining	China	Copper, Cobalt
Madagascar	Sumitomo Corp	Japan	Nickel, Cobalt
Namibia	Vedanta Resources	India	Zinc
	Dundee Precious Metal	Canada	Copper
	Trevali Mining Corporation	Canada	Zinc
South Africa	Anglo American Group PLC	US	Iron Ore
	African Rainbow Mining	South Africa	Nickel
Zambia	ZCCM-IH	Zambia	Copper
	First Quantum	Zambia	Copper
	Barrick Gold	Zambia	Copper
	China Non-Ferrous Metal Mining Group (CNMC)	China	Copper
	Jinchuan Group	China	Copper
	Vedanta Resources	India	Copper
	EMR Capital Resources	Zambia	Copper
	Euraian Resources Group	Kazakhtan	Copper, Cobalt
Zimbabwe	Zimbabwe Mining Development Corporation (ZMDC)	Zimbabwe	Copper
	Bindura Nickel Corporation (BNC)	Zambia	Nickel

Source: GIZ (2023)

Potential Demand Creation

From the DNI data depicted in Figure 6.4, we can see that Namibia has the highest opportunity for solar PV utilization as it has the highest solar irradiance, following by South Africa, Lesotho, Botswana, and Madagascar. It indicates a room for PV system installation as energy generation source to fulfilling the energy demand in those countries, which lead to the demand creation in the downstream segment. Moreover, policies like local content requirement in **South Africa** and rural electrification targets & programs in **all SADC country members**, potentially open-up more demand in PV sector.

Ease of Doing Business

Within the Sub-Saharan Africa, Mauritius ranks in number one in term of the 'ease of doing business'. Table 6.7 shows the rank of 'ease doing business' in SADC. To start a business in **Mauritius**, it only requires five working days with only USD 20,5/kWh to access electricity. Meanwhile, in **South Africa**, it requires 40 days to start a business with a relative cheaper electricity at USD 16,1/kWh. Now, compare to **DRC** that ranked at the bottom, it only require 7 days to start a business. However, the rank shrinks for the trading across border, where it requires 296 hours and 336 hours to export and import, marking a third of the average trading-boarder compliance in SSA. Though that makes it easier for a company to invest in a new business in DRC, however, the company might be struggling in the operational period.

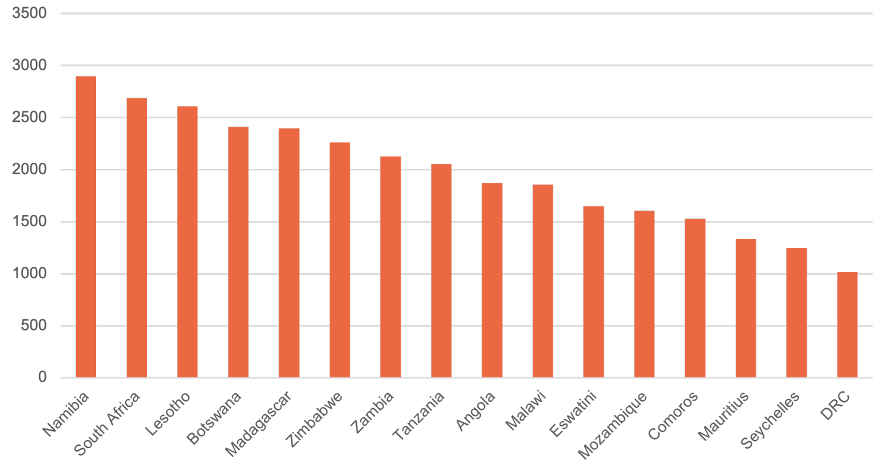

Figure 6.4: Direct Normal Irradiation in SADC
Source: Author's own compilation based on the data from (https://globalsolaratlas.info/map)

Table 6.7: Ranking of The Ease of Doing Business in SADC, within SSA Region

Country	Rank within SSA
Mauritius	1
South Africa	4
Zambia	5
Botswana	6
Seychelles	8
Namibia	9
Malawi	10
Eswatini	14
Lesotho	15
Mozambique	20
Zimbabwe	21
Tanzania	22
Comoros	30
Madagascar	31
Angola	40
Congo, Dem. Rep.	44

Source: World Bank, 2020

Labour Market

The population of working age (between 15 and 64 in SADC countries (exc. Seychelles) was 195 million in 2019. From this, 76,2% were economically active, creating a labour force of 149 million. Labour force participation rates vary considerably across countries, as Table 6.8 shows.

Moreover, following the UN Human Development Indext (HDI), we can see the combination score of health, education, and standard of living. It measures a nation's progress beyond just economic growth, but the level of human development. In SADC region, **Mauritius, Seychelles, Botswana,** and **South Africa**, scored for more than 0,700. It means that those countries scores higher than the median for SADC countries in 0,580. Only Mauritius and Seychelles that have HDI values above the world median. Between 0,600 and 0,699, there is **Namibia** and **Eswatini**. The rest, **Zambia, Angola, Zimbabwe, Comoros, Tanzania, Madagascar, Lesotho, Malawi, DRC**, and **Mozambique** scored below 0,599.

In renewable energy sector, most SADC member states lack the local capacity and technical skills to condust renewable energy resources assessments, financial modeling, market studies and develop project information memorandums. In the early stages of renewable energy development, countries such as **South Africa** depended heavily on international technical and legal expertise to strengthen the capacity of both government and private actors. Even after more than a decade of progress in renewable energy across southern Africa, many member states still lack sufficient technical expertise

Table 6.8: Labour Market in SADC

LFPR*	Countries
80% and above	Zimbabwe, Madagascar, Tanzania, Angola, Mozambique, Botswana, Malawi
70-79,9%	Lesotho, Zambia
60-69,9%	Mauritius, DRC, Namibia, South Africa
below 60%	Eswatini, Comoros

*Labor Force Participation Rate
Source: Helen Suzman Foundation (2022)

and continue to rely on skills sourced from South Africa or other developed countries (Musasike et al., 2024). According to Ciceu et al. (2025), **Zambia** has set a target to train 10,000 young people in solar technology by 2025. **Angola**'s upcoming large-scale solar and wind projects are expected to generate about 20,000 jobs by 2030, while **Botswana**'s solar programs could create around 5,000 employment opportunities within the next ten years.

Financial Sources

All SADC members listed in Appendix .2 have at least one development bank that part of the SADC DFI network (except Comoros). It highlights that at least one financial institute is ready to support the development of PV sector once the government regulate the sector. The region can also relies on donor funding for renewable energy diffusion.

Angola implements several instrument to improve business environment, fiscal reform and financial sector reforms. One of those is enabling access to finance for private investment in the production and marketing chain 54 basic goods and other priority goods of national origin. In 2020, 46 projects have been submitted to commercial banks (SADC, 2019b).

SADC (2021a) also notes that the 2019 Eswatini State of Financial Inclusion Report, based on the FinScope Survey, shows that Eswatini ranks among the most financially included nations within the SADC region. In 2019, Eswatini introduced the National Financial Inclusion Strategy (2017–2022), designed to strengthen collaboration between policymakers, regulators, financial institutions, and mobile operators to expand access to financial services for SMEs, microbusinesses, and the wider population. To oversee its implementation, the government and its partners created the Centre for Financial Inclusion (CFI) to coordinate all financial inclusion initiatives. The government of **Madagascar** is also trying to promote financial inclusion through the implementation of the National Financial Inclusion Strategy.

In **Malawi**, the government plans to continue advancing Public Finance Management (PFM) reforms aimed at strengthening revenue mobilization and controlling public spending. Borrowing will be aligned with social development and poverty reduction goals, while ensuring medium- to long-term debt sustainability. A comprehensive medium-term debt strategy has already been developed and will be regularly updated to remain effective. The government of **Mozambique** will also continue to facilitating access to finance by SMEs, improving and being transparant in management of debt and public finance, and reforming its financial sector.

6.2.2. The Role of Regional Institutions

This section of analysis will explore the role of regional institutions in the SADC region concerning the integration of solar PV value chain within the region. Alongside with its role, the embedded challenges will be analyzed.

SADC is a regional group that sees integration as a key step toward improving the country member's development. As noted by SADC (2019b), the goal of regional integration is to support sustainable and fair economic growth by strengthening production systems, increasing cooperation, promoting good governance, and maintaining lasting peace and security. In terms of integrating the solar PV value chain, there appears to be no specific regulation or official guidance from SADC institutions that directly supports or legitimizes this process within the region. However, broader strategies related to industrialization and the transition to renewable energy have been published and are recognized as key priorities within SADC's regional integration agenda.

One of the most important plans is the SADC Industrialization Strategy and Roadmap (2015–2063), which will be further explored in this section. It plays a central role in promoting economic and technological progress across the region, aligning with the African Union's Agenda 2063. SADC prioritizes industrial growth and market integration by supporting sustainable industrialization, boosting competitiveness and production, allowing free movement of goods and services, encouraging macroeconomic stability, improving financial and monetary cooperation, and attracting both regional and international investment to deepen integration (SADC, 2019b).

Moreover, SADC has a number of legal and policy instruments to guide the devlopment of renewable energies in the region, including SADC Energy Protocol (1996); Revised RISDP (2015-2020); Regional Infrastructure Development Master Plan: Energy Sector Plan(2012); Regional Energy Access Strategy and Action Plan; and AU Agenda 2063 (SADC, 2018). Some of the regional bodies concerning in the renewable energy transition, including PV technology are depicted in Table 6.9.

Table 6.9: SADC Renewable Energy Bodies

Institutions	Establishmemt	Description
SADC Centre for Renewable Energy and Energy Efficiency (SACREEE)	2016	A regional body to support and track the progress of the Renewable Energy and Energy Efficiency Strategy and Action Plan (REEESAP). Its goal is to help expand access to modern energy and strengthen energy security in the SADC region by promoting the use of renewable energy, energy-efficient technologies, and related services through market-driven approaches.
Regional Electricity Regulators Association of Southern Africa (RERA)	2002	Formed by the SADC Ministers of Energy to harmonize the regulatory framework as well as provide a conducive environment for investment in the region's power sector.
Southern African Power Pool (SAPP)	1995	A regional organization that helps SADC member utilities work together in planning, generating, transmitting, and trading electricity. It allows countries to buy and sell electricity to each other through a competitive market system.

Source: SADC (2018)

SADC countries can better use their energy resources by working together under common rules and clear policies on things like energy pricing, planning, cross-border trade, and support for renewable energy and small businesses (Mutanga & Simelane, 2015). When countries align their efforts, the energy sector can help drive industrial growth and development across the region. The SADC Industrialization Strategy also highlights the need to involve the private sector by building trust, improving infrastructure, developing skills, and making finance more accessible (SADC, 2019b). As noted by Black et al. (2020), regional integration can grow faster when private sectors actively pushes governments to improve market access and reduce trade barriers. At the same time, governments must work closely with stakeholders to support supplier development so that more firms can participate in and benefit from these regional value chains.

Despite the availability of various policy frameworks and the potential for public-private partnerships to support solar PV value chain integration in the SADC region, several challenges remain. Although regional strategies (e.g. the Protocol on Industry, regional value chain profiling, infrastructure development plans, and the Regional Mining Vision, etc.), provide a solid foundation, the main difficulty lies in getting individual countries to implement them effectively. According to SADC (2019b), many SADC member states lack the capacity or flexibility to adapt to fast-changing global trade and production systems. This misalignment between national and regional priorities often slows down progress.

Moreover, empirical study in mining sector conclude that a fragmented approach makes regional integration difficult to achieve the economic scale and investment needed to compete in more advanced mining-related industries. There is a conflict between national polities and the need for a regional approach in the mining sector in SADC region. Although it makes strong economic sense to integrate mining capabilities and resources across the region, many countries focus on narrow, local interests, such as local content requirements that limit cross-border cooperation (Arndt & Roberts, 2018).

6.2.3. The Role of International Institutions and FDI

As the interconnectedness of regional trades and production networks plays a key role in enabling GVCs, we argue that international institutions and FDI should be considered essential external drivers of the regional PV value chain. Nation's capabilities and regional institutions alone may not be enough to fully regionalize the PV value chain, making external support crucial. This section explores the roles of those drivers and the challenges they face in supporting regionalization efforts in the SADC region.

Most SADC member states still rely heavily on donor funding in order to unlock economic opportunity. One of the most reliable donor and technical assistance is from international development institutions like World Bank. Malawi developing a solar map with a support from the World Bank's Energy Sector Management Assistance Programme (ESMAP) (Jadhav et al., 2017). Moreover, two solar PV power projects in Zambia received funding from International Finance Corporation (IFC) of the World Bank Group (Jadhav et al., 2017).

On the other hand, international assistance also comes from bilateral cooperation with foreign countries. There is a strong ties between SADC and German government through the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. For example, through the technical study in mineral sector (GIZ, 2023). Another bilateral cooperation also happens with China through the BRI partnership, particularly in the mining sector (Escobar et al., 2025).

While the reliance to donor funding is dominated in the region, once that comes to an end it is critical that the private sector steps in to ensure that sustained benefit accrues. SADC (2017) put FDI as an external factor that can help the region to close the financial gap. However, to maximize the effects, there should be a proactive approach from the country. It is important for a country to be open in FDI, as opennes to inward FDI boosts both forward and backward integration. For instance, by establihing EPZs or SEZs, it will attract both FDI and domestic investment. In line with UNCTAD (2019), noted that in developing economies, the primary aim of SEZs is generally to build, diversify and upgrade industries by attracting FDI.

In SADC, according to SADC (2017), there is approximately one fifth of investment in the region that funded from FDI, primarily those in productive objects. In the projected financing gap for 2015-2030, depicted in Table 6.10, shows the contribution of FDI towards GDP in every SADC country member.

Table 6.10: Contribution of FDI to SADC's GDP

Country	FDI (% of GDP)
Angola	6,0
Botswana	4,6
DRC	3,1
Lesotho	3,4
Madagascar	5,5
Malawi	2,6
Mauritius	2,3
Mozambique	5,5
Namibia	2,8
Seychelles	11,7
South Africa	1,9
Swaziland	2,6
Tanzania	3,8
Zambia	5,8
Zimbabwe	0,8
mean	4,2
median	3,4

Source: SADC (2017)

FDI offers benefits to the country member. For instance, logistics development is seen as a key driver of inclusive growth in Namibia, particularly through the Port of Walvis Bay and its transport corridors. FDI has been central to building and operating this infrastructure (Bertelsmann-Scott, 2018). Furthermore, the paper suggests that Namibia should adopt a flexible approach to FDI—while sectors like extractives allow for stronger negotiation on joint ventures and skills transfer, areas such as manufacturing offer less room for this. Since infrastructure is vital for long-term development, overly strict FDI rules could discourage investors and limit future benefits.

6.3. Answering SRQ 2: Socio-Technical Factors Affecting the Integration of PV Value Chain in the SADC Region

Before moving into the discussion, it's important to mention that this analysis is based on the limited number of studies that specifically examine solar PV development at the regional level within SADC. Therefore, some of the results particularly in the Innovation System Assessment are representing more into one country case, such as the domination of PV installation projects in South Africa. While these examples still provide insights into the broader SADC solar PV value chain, they may only represent a small part of the overall regional picture.

The innovation system in the solar PV value chain within the SADC region presents two key paradoxes. We could see a strong fulfillment in the downstream segment, where more solar panels are being installed and bring clean energy sources to the communities and business in the region. However, on the other side, the region is still struggling with manufacturing the PV components to meet the demand. Moreover, while several directions were provided from the top institutions, yet it still lack on the national implementations.

6.3.1. Factors supporting regional PV value chain integration

The reason to see solar PV plants in the region is because there are active orchestration from the government in the regional level or in the country-level.

1. **Strong guidance from the top-level of institution**
   The TIS analysis reveals an expectional high scores for guidance of search. This is a result of clear, top-down policy signals. For instance, international commitments like Paris Agreement created the initial momentum, which was translated into policy frameworks and programs, like the REEESAP, Industrialization Strategy and Roadmap, Regional Indicative Strategic Development Plan, and many more in the regional level. These regional strategy then being transated and adopted in every member country.
2. **Potential demand creation and capital attraction**
   The strong policy guidance directly enabled market formation. Competitive auctions in South Africa and Namibia, financial rebates in Seychelles, and the introduction of a carbon tax in South Africa have stimulated demand, leading to a rapid increase in installed capacity from near-zero to several gigawatts (Figure 6.3). This market has been fueled by effective resource mobilization. International donors, multilateral banks like the World Bank, and private Independent Power Producers (IPPs) have provided capital into the region, as evidenced by the successful public-private partnership for Namibia's Omburu solar project. Moreover, since most of SADC countries have a high to very high solar irradiance, making the solar PV technology as the most prominent technology to generate electricity, and therefore potentially create market in PV system installation in every country in SADC.
3. **Available donor funding and bilateral cooperation**
   Most of SADC countries, their first solar PV installation projects mostly were supported by donor funding, such as from the World Bank. Moreover, bilateral cooperation between some of the country members with foreign country provided technical and financial assistance to the industrialization progress. For instance, the partnership between China and DRC helped the country to extract mineral resources. However, while donor funding provided opportunity to create more demand in the PV system installation, it is also important to still develop country's own investment strategies to sustain the financing scheme in PV sector development.
4. **Abundant mineral resource and operationalized mining companies in DRC and Zambia**
   Not only rich in minerals, these countries also have several key players in mining business both from local and foreign companies. While in Zambia, the players are dominating by Zambian

companies, in DRC it is more dominating by Chinese companies. It also relevant with the strong ties between China and DRC, particularly in mining sector. In Addition, these countries relatively have a better rank in the 'ease of doing business'. Zambia ranked at 5 among other SSA countries. Meanwhile in DRC, even if it ranked at the bottom, yet it only needs 7 days to start a business in the country.

Nevertheless, to move from just extraction industries toward more value added manufacturing (refinery), it requires huge amount of electricity and skilled labour due to the high technical demand in the upstream manufacturing. In DRC, there is only 14% of its population that had access to electricity and industry sector used 16% of energy consumption, while in Zambia is only 28% and 32%, respectively in 2018. Moreover, the countries remain struggling in providing high-skilled labour, considering the low HDI index (below 0,5999 out of 1).

5. **Fulfilled electricity access and ease of doing business in Mauritius, Seychelles, and Eswatini**
   Mauritius and Seychelles are the only two countries in the region that successfully fulfilled 100% electricity access for their people. Each has relatively high share of industry in energy consumption with 26% and 28%. Despite because of their small island and population factors, the fact that in Seychelles has highest share of manufacturing in their GDP, could mean that it has the capacity to push the growth of manufacturing sector. Both countries also recorded themselves as the best performance in the ease of doing business among other SADC countries. Moreover, the HDI index in those countries is remarkably high, with more than 0,700 score. Furthermore, Eswatini with its 65% electricity access and 56% energy consumption for industrial sector, signing for a strong industrial capacity and readiness for further manufacturing. The rank of its ease of doing business is not that significant, with only ranked on the 14th among SSA countries.
6. **Developed business ecosystem in South Africa**
   South Africa, has the most outstanding competitiveness among other countries in SADC. First of all, the country shows a succeed strategy in managing the SEZs, maximizing the port and logistic infrastructure. This makes the industries operate within the SEZs has better connection with global and intra Africa market. Second of all, around 86% of its people had access to electricity, and industry sector consumed for 39% of total energy. Meaning that the country relatively better in providing electricity for the population and manufacturing.

   Moreover, the country is a home for around 70 manufacturers, operating in midstream and downstream segments. Among the other SADC member states, South Africa is considered as a country with more availability in skilled-labour, with DNI score more than 0,700 and the fact that the country's pioneering the development of renewable energy sector. Beyong those factors, it is also because it has a good performance in ease of doing business and the potential of demand creation through the government's intervention. For instance, the presence of such as the local content policies, though it's not perfect.

6.3.2. Factors hampering regional PV value chain integration

Challenges are found more in the manufacturing sectors (upstream and midstream). These barriers such as the deficit of knowledge and technological know-how, policy misalignment, and structural economic challenges.

1. **Major skills gap in most SADC countries**
   Even though there are many private PV installers and developers entered SADC's market, yet not many capital- and knowledge-intensive manufacturers entering the region. While there are abundant minerals potential for PV manufacturing, however the region is lacking on the capacity to further processing it. With 195 million labour market in 2019 among SADC countries, only Mauritius and Seychelles that have HDI values above the world median.
2. **Policy and institutional misalignment**
   A conflict between national-level policies and the regional-level integration often slowing down the progress. The report identifies that while regional strategies for industrialization exist, countries often focus on narrow and local interests like local content requirements that, in contrast, limit cross-border cooperation. Sometimes, the rules that intented to help were actually hindering

the progress. For instance, the TIS analysis of the midstream highlights that ”unclear definition of local content requirements” (F4-d) and ”inadequate enforcement” (F7-d) led foreign firms like Trina Solar to cancel investment plans. Instead of fostering high-value manufacturing, these rules encouraged low-value assembly or were simply bypassed. There is also a clash in goals. On one hand, the government wants the ”cheapest cost energy” for its people. On the other, it wants to build a local industry. But a new local factory can't possibly compete with the low prices of mass-produced panels from overseas. This conflict has meant that cheap imports almost always win, starving local manufacturing of a market.

3. **Lack of connectivity in transportation infrastructure** In the regional level, there remain a challenge in connecting the transportation mode within the region. Large numbers of road trucks in the port terminal area often interfere with port operations and harm performance. Moreover, most of the ports are surrounded by densely populated and highly industrialised zones, with little or no room for the necessary expansion to handle high port volumes. Road access to the ports is also often through highly developed business, industrial and residential areas subject to severe traffic congestion.

4. **Practical barriers**
   Beyond the systemic challenges, there are also technical challenge in implementing the regional integration for solar PV value chain. The expert interview highlights a crucial ”inhibiting factor”, where the best solar resources are often located in remote regions with low energy demand (e.g. South Africa's Northern Cape). Without fully leveraging regional grids like SAPP to connect production centers with demand centers across borders, this solar energy potential remains underused and economically inefficient.

   > The biggest challenges with PV power generation is the solar availability. You need to match the demand for energy with power production ..... like I say in South Africa, we have solar PV in a region where there's no demand and you've got to put your transmission all the way there. Whereas if you can tap into the SAPP and you're going to demand closer and then you use other various kind of instruments, so different countries will have hydropower as a balancing network can definitely facilitate that overall implementation of PV. - (A1)

   Furthermore, the challenge lies in the lack of end-of-life management. The value chain is conceived as a linear process, driven purely by the cheapest cost per kilowatt output. There is no incentive for circular design, repairability, or recycling. Damaged panels are simply dumped, representing a future environmental burden and a missed economic opportunity for a value chain based on refurbishment and material recovery.

   > So what happens is the people who are adopting PV system technonology, such as the IPPs ..... are just looking for the cheapest cost (cheapest price per kilowatt output). When you are just driven by a cheapest cost, what happens next is there's no incentive when you look at circularity. They don't care about what will happens to the product at the end of life.....So let's say if a glass panel is damaged now currently, that panel is basically dumped, ... It's not designed in such a way that one can easily just remove the glass panel, replace it or reside seating or something. - (A1)

7
Comparison Analysis: Learning from China

This chapter is organized to compare the innovation system performance between China and the SADC region, followed by identifying lessons learned from China's strategic interventions in developing its solar PV value chain that can be applied to the SADC context. The chapter concludes by addressing the third sub-research question.

7.1. Comparison of the SADC and Chinese PV TIS

In this section, we examine the differences between how China and the SADC region have developed their solar PV TIS. China's PV TIS is analyzed from the perspective of a single state, whereas the SADC represents a group of member countries with varying capacities and policy environments. Although this may not be a direct, one-to-one comparison at the country level, both analyses consider the internal and external factors affecting the functions performance such as export-import activities, international guidance, and foreign market dynamics. Therefore, the comparison remains valid and meaningful for drawing lessons, particularly in understanding how the systemic interventions can support PV value chain development.

Overall, China's strong state coordination, combined with private sector initiatives, has played a key role in advancing the solar PV value chain across all segments. In contrast, the SADC region has largely relied on support from international organizations and foreign investment, with solar PV projects often funded and guided through donor-driven programs. A more detailed comparison of each system function is presented in Table 7.1.

7.2. Answering SRQ 3: Lessons can be Drawn from Chinese Case to SADC Case

Comparing how China and SADC developed their solar PV sectors shows that their progress has been shaped by different systems and ways of working. The SADC region can find useful ideas to grow its own regional solar PV value chain by learning from China's experience, especially the key decisions and drivers behind its success. Some of the main lessons include the need for strong government support, smart choices about where to focus in the value chain, better infrastructure, and working together as a region to build shared strength.

7.2.1. Lesson 1: The power of proactive orchestration with decentralized implementation

One of the key lessons from China's success is the role of the government in actively orchestrating the long-term and dynamic regulations and programs. The analysis in chapter 5 highlights that guidance of search and creation of legitimacy were the strongest functions in China's PV TIS. However, this was not simply a rigid and top-down approach. It blended the centralized strategic direction and decentralized implementation, a model that can be a key lesson for the SADC's regional-to-national governance structure.

In China, the central government set the overarching vision through its Five-Year Plans and national

Table 7.1: Comparison between PV TIS in the SADC and in China

Funtion	Fulfillment in SADC region	Fulfillment in China
F1- Entrepreneurial activities	Activity is concentrated in the downstream segment within PV system installation, often dominated by foreign companies and state utilities than local entrepreneurial base.	Mainly driven by privately-owned companies, esp. in manufacturing sector, with government policies enabling private enterprise and profit motives drive rapid growth in firms and production capacity.
F2- Knowledge development	Dominated by feasibility studies for specific pilot projects, with a lack of dedicated local R&D centers.	Initiated with technology import for industry operational and research projects, following with internal technology advancing through R&D investment and high-skilled talent. Combined with learning by doing from the policy adaptation.
F3- Knowedge exchange	Knowledge is transferred by foreign firms, mostly some basic operational know-how (low-tech).	Relied on imported PV machinery and complex PV components at the earliest stage, moved on to the active R&D projects and investment to build local production capabilities.
F4- Guidance of search	High-level policy direction from regional plans to support member countries accelerate energy transition. Yet, some policies remain unclear and poorly enforced local content rules.	The state to actively guide and shape the growth of the entire solar PV value chain with clear, steady, and long-term guidance through its Five-Year Plans, targeted industry programs, and national strategies.
F5- Market formation	Successful market creation for PV installation through competitive government auctions, but still very little demand for locally manufactured components.	From export oriented to oversupply that led to domestic demand creation using demand-side policies like FIT and subsidies.
F6- Resource mobilization	Available capital mostly from international donors, development banks and public-private partnerships for solar farm development. With skilled labour shortage and local capital for manufacturing base.	Combined government investment, state-backed loans, tax incentives, private entrepreneurial capital and infrastructure support to suport the entire PV value chains.
F7- Creation of legitimacy	Available public and political support promoted by regional bodies and international climate agreements, with poor standard-/progra implementation	PV technology was legitimized through high-level government promotion, its inclusion in strategic national plans, the formation of powerful industry alliances that lobbied for support, and its alignment with national energy security and environmental goals.

Source: Author's own compilation

industrial policies, providing a stable and predictable environment for investors. It then empowered and incentivized provincial and local governments to execute this vision. Local policies were directly aligned with central government priorities, and local governments had the autonomy to offer specific incentives, streamline permits, and grant preferential treatment to attract PV industries. This created a competitive, yet aligned, dynamic where provinces vied to become leaders in the sector, accelerating national goals through localized action.

For SADC, where the regional bodies act as the regional coordinator and the member countries are responsible for putting plans into action. The main issue isn't the lack of regional strategies, like the REEESAP, but rather the gap between planning and doing. Many regional goals are not fully carried out because national policies are often uncoordinated, and each country may prioritize its own interests over shared commitments.

The lesson is for regional institutions in SADC, to move from strategy-passive enablers to active orchestrators. The regional vision must be translated into concrete, non-negotiable goals for the entire points of protocol such as the local content requirements and the manufacturing capacity target, to provide central guidelines. Moreover, the framework also need to provide the countries member with flexibility, technical support and financial mechanisms to achieve those regional targets within their national contexts. This mirrors how Chinese province implemented its central policy. Furthermore, SADC can create platforms for sharing best practices and even foster healthy competition among member states to attract investment for specific parts of the value chain, ensuring that national actions contribute to a regional integration.

7.2.2. Lesson 2: From low-tech import to local capability building

China did not attempt to dominate the entire PV value chain simultaneously. Its approach was sequenced and strategic. As detailed in chapter 5, China first focused on the segment with a lower technological barriers, and leveraged its advantage in labor costs. Only after establishing a dominant position, then they moved aggressively into the capital- and technology-intensive upstream segment (polysilicon and wafers), backed by massive state-led financial support.

For SADC region, where the upstream and midstream segments are particularly weak, the lesson is to adopt a similar approach tailored to its own strengths. As the interview findings suggest that competing head-to-head with China in the main production activities within the PV value chain (e.g. solar cells and modules; polysilicon and wafers) is currently unfeasible. Instead, the SADC could focus on:

1. Build capabilities in manufacturing supporting components where the barrier to entry is lower, such as mounting structures, cables, inverters, and battery pack assembly for energy storage systems. While it can potentially take a share in the global PV value chain, it can also fulfilling the local content requirement.
2. The region is rich in the raw materials China lacks, such as copper and cobalt. Instead of exporting these materials in raw forms, SADC can learn from China's own strategy of capturing value. The focus should be on developing regional refining and processing capabilities, turning raw mineral into higher-value intermediate goods. While also maximizing the potential value of China's BRI partnership.
3. Continue to expand the downstream installation market through programs like competitive auctions. A strong and growing domestic demand for PV systems creates the essential demand pull needed to justify future investments in local manufacturing.

7.2.3. Lesson 3: Diversified domestic financial ecosystem

China utilized a combination of government investments, state-backed loans, tax incentives, and private entrepreneurial capital to support the development of entire PV value chain. SADC region, meanwhile, resourced their capital from international donors, development banks and public-private partnerships for solar farm development. More concentrated on the downstream (PV installation projects), and leaves a gap in the manufacturing sectors.

An industrial strategy cannot be funded by project-based foreign aid alone. SADC must utilize its regional and national financial mechanisms, such as regional development banks, sovereign wealth funds, or targeted industrial loans, that can provide the patient, risk-tolerant capital needed to build factories and support a manufacturing ecosystem. According toNygaard et al. (2017), a shift from direct donor support for projects to the development of enabling frameworks that foster market-based diffusion, emphasizing the need for institutional and personal transitions among stakeholders to become 'enabling-framework specialists'.

7.2.4. Lesson 4: Building integrated infrastructure

China's manufacturing leadership was built on a foundation of targeted infrastructure, with agglomeration manufacturing hubs. Through its coal based power, China gain competitiveness in low cost industrial electricity. Most recently China has begun shifting the production of high-carbon intensive to provinces with abundant hydropower, demonstrating an agile response to global demands for lower-carbon products. Moreover, China leveraged its existing strengths by clustering midstream and downstream manufacturing in coastal provinces, to give manufacturers direct access to highly efficient ports and dense transport networks. Furthermore, to remain competitive, China's also allocate their resources to build strong R&D centers and recruiting high-skilled labor.

The situation in SADC region as revealed in the analysis is the opposite of China's success. Most of the countries in SADC region still lack of electricity capacity, with only Angola, Mozambique, South Africa, and Zambia that have excess power generation (SADC, 2018). The lesson is to think of infractructures as an integrated ecosystem. SADC region can be better at utilizing the SAPP in transmiting electricity from abundant power generation to industrial hubs across borders. While coal is still dominating the energy sources in the region, it can be combined and maximized with other renewable energy sources like wind, hydro and solar to provide electricity to the industrial sites. Moreover, the region can establish shared R&D and vocational training centers focused on solar technologies. This would create the skilled workforce needed for manufacturing and reduce reliance on importing foreign expertise, a key weakness identified in the previous chapter. With FDI resources, the region can also utilize the investment to develop its transportation and logistic connectivity.

7.2.5. Lesson 5: Rural electrification program to create demand

China's rural electrification program deliberately created large-scale, coordinated demand for PV by rolling out electrification across hundreds of villages with PV integrated alongside other renewables. Although the total installed capacity (e.g. only 12 MW) was small compared to national demand, the program showed that decentralizing renewable options and targeting off-grid villages systematically can expand rural electrification faster and more sustainably. This also guaranteed the demand stimulation in the downstream segment of the PV value chain (PV system installation).

For SADC, the lesson is that relying mainly on its rural electrification target, where it can also combine several PV programs and other option of renewables. markets limits the ability to scale the PV value chain. For example, by bundling village mini-grids, public facilities, and hybrid systems. Also, to mobilize national and private investment, rather than just relying on the donor funding from international organizations. This would directly stimulate downstream PV deployment, attract private sector participation, and eventually feed back into local manufacturing and services, supporting the growth of the regional PV value chain.

8 Discussions

The chapter discusses the study's main findings, providing answers to the main research question guiding this thesis: ”What are the strategic interventions for the SADC region to develop a regional solar PV value chain?”, showing the practical implication of this study. Additionally, it explores the theoretical implications of the findings towards the regional PV value chain operationalization strategies. Lastly, limitations on this research and future research recommendations are explored in this chapter.

8.1. Discussion of Findings

The TIS assessment resulting a list of factors that hindering and supporting the development of PV sector within each case study. The results then being compared, and were analyzed to draw a lesson learned. It is known that both cases have a strong functions performance in downstream segment and particularly in the guidance of search. While China relatively has a balance performance in all segments, including the downstream, midstream, and upstream segment of value chain. In SADC region, the gap quite significant (seeing the range of colour shades between the three segments). In China, while government also plays a key important role, the development of PV sectors combining more broaden factors. From the means of driving sector privatization; mobilizing many policies, programs, several financing schemes, and local government's commitments towards the development of the sectors in all segments; to the high-technology, knowledge, and financial sources from foreign companies and countries.

In SADC, the drivers of PV innovation are narrowed into two: The strong guidance from top-level instititutions and the potential demand creation. The government auction programs in several countries are proven as an effective way to involving the participation of private sector (IPPs) in PV system deployment, even if the demand for locally manufactured components are still limited. This finding was confirmed by the respondent, who is an expert in renewable energy and circular economy in SADC.

> In terms of from where we started 10 years ago in South Africa in terms of creating and enabling environment, we developed that renewable IPP programme which has been a success story not just in Southern African region but also globally.....it received many awards and is recognized for the initiative..... - (A1)

Another key factors that drive the development of PV sector in SADC region is the demand creation that mostly happened through the rural electrification programs and auctions programs. The use of PV systems in the deployment mostly coming from imported components from China. It is align with the concept of backward linkage in GVC, where it entails the use of imported intermediate inputs to produce locally. According to Dine (2019), manufacturing sectors are seen to grow faster through the backward linkages. The demand creation factor is being confirmed by the expert, saying that the demand creation will eventually help the technology to reach its economies of scale, therefore will attract more players to the industry.

> From an affordability point of view, if the integration of solar PV happens, so the use of micro-grids can happen at rural and regional level. People will pay for it because they currently are paying for it anyways. Then it will eventually create more demand on the device and reduce the cost... - (A1)

However, continuously relying on the imported intermediary products wouldn't be sustaining the country's competitiveness. Therefore, building local (in this context regional) production capacities is necessary.

In SADC, while some activities are presence in supporting the development of PV, those remain some rooms for improvement. For instance, while the PV local content rules regulated by the the government to foster local industry, however the regulation left loopholes that lead to ineffective regulation and confusion in the implementation. Foreign firms engage in low-tech assembly rather than deep technology transfer. The interview validates this, stating that:

> Knowledge diffusion was very limited ..... it was the same Chinese individuals who the Chinese OEMs brought through here, who was doing the final assembly in country. So the knowledge diffusion was very limited in my opinion. - (A1)

After the TIS performance assessment where we see the intersection of actor, network, and institutions in activating the functions, the next step would be analyzing the regional PV value chain design factors. It involved the design factors analysis and institutional analysis. The result from Chinese case would be used as additional insights to draw lessons, while the result from the SADC's case would be used to designing the regional PV value chain in the region.

This research found that SADC region still facing some challenges in developing competitiveness in PV manufacturing sector, including the major skills gap and policy misalignment. In mining sector for example, while DRC and Zambia have the capacity to extract the minerals, however it's hard for them to move ahead towards refinery sector since it requires high-technicality capabilities. Moreover, instead of operating in the main PV value chain actors (except module assembly), most of the companies in SADC are operating in the supporting, such as the manuf acting of PV component and production tool. The expert confirmed that it's going to be hard for solar PV manufacturing in SADC to compete apple-to-apple with China, considering the challenges it has.

> So as much as we may have access to these critical raw materials that goes into PV production, we can't compete in a manufacturing scale.... I think China's a lot more advanced and ahead of that curve. - (A1)

Without neglecting the challenges that remains in the region. Some of the countries have an outstanding competitiveness factors that potentially fill in the gap in PV value chain within the region. The design process is considering both challenges and opportunities. We suggest that regionalizing PV value chain in SADC region could start from just several countries with outstanding performance in the design factors, while the remains can act as consumer based. Therefore, the design of the PV value chain integration would be follow as bellow.

- **South Africa** as the main actor in **Midstream** and **Downstream** manufacturing, particularly in module assembly, production machinery, and PV component (e.g. inverter, battery, mounting system, cable, and connector). The country should focus on strengthening the available manufacturing segments, rather than shifting to the main PV value chain since it would be hard to compete with China. It already hosts the majority of SADC's PV manufacturers and has a relatively mature industrial base. Its competitive advantage lies in well-developed Special Economic Zones (SEZs) and strong transport and logistics infrastructure, offering access both to the global market via ports and to the wider African market through road and rail networks. This positions South Africa as the core hub for module assembly, inverter and balance-of-system production, and large-scale PV deployment.
- **Upstream segment** will be dominated by **DRC** and **Zambia** by giving value added to their mineral extraction and producing ancillary materials. In the upstream segment, DRC and Zambia hold a central position due to their abundance of mineral resources—particularly copper—as well as the presence of both local and foreign-owned mining operations. These countries already serve as the backbone of raw material extraction in the region, yet they face constraints such as limited electricity access and a shortage of skilled labour. To address these gaps, they can leverage support from neighbouring SADC member states.
- **Mauritius**, **Seychelles**, and **Eswatini** could act as buffer states within the regional value chain. These countries currently lack significant PV manufacturing industries, suggesting that their industrial focus has not been directed toward this sector. However, their competitiveness in specific areas makes them strategically important as complementary hubs. Mauritius and Seychelles,

with their competitiveness in labour market and infrastructure readiness can provide the labour supply and trade facilitation for export oriented products since it has competitiveness SEZs, electricity infrastructure, ports facilities, and the ease of doing business. Moreover, Eswatini, with its geographically closeness to DRC and Zambia could act as the buffer for energy sourcing, using the role of SAPP to facilitating the electricity transfer. This illustrates how the upstream hub in DRC and Zambia can be sustained through complementary contributions from buffer states within the region.

- The remain countries will be the main consumers and sales for the product. Since every country in the region has high to very-high solar irradiance, it gives them benefits to utilize solar as electricity source. Priority could also be made for the countries with the highest Global Competitiveness Index (GCI) ranking among SADC, which are Angola, Malawi, Namibia, South Africa, and Zimbabwe. As demand rises from these countries for solar PV, then they could absorb the PV components from South Africa's production, in the mean time demand for the glass, frame, and other ancillary materials would be coming from foreign companies, since there is no production capacity to absorb that materials from local (regional) industries. Then, SADC countries will eventually participate in the RVC and GVC.

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Finally, to operationalize that design, the involvement of regional, national, and international institutions are necessary. As noted in the SADC Industrialization Strategy and Road Map 2015-2063, that within the transformational strategic, institutions play as key enables. Makalima et al. (2024) suggest that countries with strong institutional frameworks attract more capital inflows, fostering conditions conducive to private sector growth and foreign investment.

Country-level institutions should facilitate the localization of the industry, through providing innovative financing schemes, not only utilizing the donor funding availables but also combining it with other financial incentive scenarios. It should act both as regulator and implementer in the country as well as a facilitator that bridge the regional direction with local circumstances. The institutions, particularly in South Africa, DRC, and Zambia should encourage the business sectors to moving forward into more high-tech PV manufacture, by facilitating technology and knowledge import and diffusion. Lastly, for the national institutions in other countries should also leveraging the rural electrification program, both incorporating to the national on-grid power system and through the off-grid small PV system. It is necessary to create a massive domestic demand in PV system.

Moreover, from the regional perspective, the regional institutions should act beyond just a regulator but as an active orchestrator. It should facilitating the guideline and framework for the state's institutions to follow the direction, particularly on how to operationalize the design, thus it provide the foundation layer in the regional PV value chain. To strengthen the connectivity of the transport and logistic infrastructure, the related ministry in SADC should actively and communicating and mobilizing resources to improve the hard infrastructure. Moreover, regional institutions also should orchestrating the labour market exchange and intra-regional trade. Finally, SAPP as regional power pool should actively managing the electricity supply-demand to support the industrialization in the prioritize countries.

Finally, the international institutions and FDI are indeed play a key important role in supporting the state's economics and program implementation. FDI empirically showed a contribution to the country's GDP. In the long run, when the national and regional institutions able to provide a learning-ecosystem, the role of FDI would be beyond just short-term economic benefit, but also long-term economic benefits such as the improvement of HDI and the advancement of PV technology. It should be pushed, especially in DRC and Zambia where the sector productions require high-technicality capabilities. International institutions, like World Bank should provide more donor funding to various countries in SADC, especially to achieve the rural electrification target. Technical assistance should also be provided to spread the technology know-how, which most likely the low-technology one.

8.2. Theoretical Implications

The findings of this research contribute to the theroretical understanding of regional value chain, particularly in solar PV sector in developing countries. The research underscores the importance of institutions (including state's institutions, regional institutions, international institutions, and FDI) in regionalizing solar PV value chain. It is empirically explore the roles of each institution, the SADC itself mentioning the role of regional institutions in their regional industrialization, infrastructure and renewable energy pathway and franwork.

Additionally, this research also provides empirical findings on the role of innovation system performance in advancing the technology development in one geographical area, in this case is SADC region and China. Those factors are indeed contributed to the advancement of PV value chain in China until it is dominating the world. While in global south, particularly SADC that has some limitations (like human resource limitation, financial source limitation, institutions limitation, etc), those slowing the diffusion of PV technology.

Finally, the design layer is proven as an important variables to be considered in designing regional value chain. There might be several factors that can be considered in deciding the PV manufacturing location. However, we believe that the factors should at least considering the human factor, the financial factor, infrastructure factor (hard & soft), and supply-demand factor, to gain the maximum competitiveness.

To sum up, this research gathered several theories and make a link out of those, to guiding the operationalization strategy in regionalizing solar PV value chain. This contributes to the innovativeness of this research, by introducing new approach in designing regional value chain.

8.3. Limitations and Future Research

This study has several limitations that should be noted. Acknowledging them is important to have a better understanding of the context of the findings and to highlight directions for future research.

First of all, the strategic recommendations suggested in this research is merely a preliminary suggestion to start the idea of how to regionalizing solar PV value chain in SADC region. While to actually operationalizing the design of PV value chain, further feasibility studies in those particular countries are still needed to consider other technicality in building manufacturing industries. That could be the socio-economic feasibility and the environmental feasibility.

This research mainly using desk study to find empirical data around solar PV sector development in two case studies, China and SADC. In analyzing the performance of PV TIS in both cases, qualitative coding process were utilized. This method is not perfect due to it relies mostly on the researcher theme's interpretation and limited source of input papers, and therefore left a room for improvement. To minimize bias, we conducted an interview to confirm the findings from the desk study. However, it was based on a limited number of respondents. While this interview offered valuable insights, particularly for the SADC case analysis, they may not fully represent the wide range of perspectives across different types of institutions within the multilayer analytical framework. Additionally, the literature used to analyze the SADC case was limited to the availability of peer-reviewed academic papers. As a result, some of the perspectives reflect individual SADC member countries rather than the region as a whole. Although these sources provide meaningful input, they may not fully capture a unified regional viewpoint.

Moreover, sustainability-related aspects of the PV value chain are not covered in this research. Topics such as PV component recycling activities, carbon emissions from manufacturing activities, and potential labor rights violations or illegal labour issues were beyond the scope of this study and are therefore not included in the analysis. As PV waste also becomes an issue within the global PV value chain, it is also recommended to consider the circularity aspect within the value chain scope of analysis.

9 Conclusions

This thesis investigated the socio-technical and institutional factors that affecting the development of solar PV value chain in two case studies, China and SADC. The study for China is aimed for providing a lesson learned from the best practice in building and dominating solar PV value chain in the world. Moreover, the study in SADC is to understanding the region's current progress, to propose strategic recommendations in building the regional PV value chain.

Findings show that China's rise in the global PV industry was shaped by three interlinked strategies: (1) strong government orchestration and long-term planning, (2) capturing the entire value chain step by step, and (3) infrastructure-driven industrialization supported by diversified financing and technology transfer. In contrast, SADC's PV development remains fragmented. The TIS assessment revealed uneven performance across upstream, midstream, and downstream segments, with most activity concentrated in downstream deployment through auctions and rural electrification. These programs, while reliant on imported components, demonstrate that demand creation can stimulate market growth and eventually feed back into manufacturing opportunities.

Comparing both cases, the research identifies several lessons for SADC:

- Proactive but flexible orchestration at the regional level is needed to balance diverse national interests.
- Building local capabilities should start with segments that have lower entry barriers (e.g., module assembly, balance-of-system components).
- A stronger and more diversified domestic financial ecosystem is required to reduce dependence on donor funding.
- Integrated infrastructure and logistics are essential to reduce costs and improve competitiveness.
- Rural electrification can serve as an anchor market, driving consistent demand in the downstream segment and supporting upstream and midstream growth.

From these insights, the thesis proposes that SADC's strategic interventions should involve aligning regional institutions as active orchestrators, encouraging country-level institutions (especially South Africa, DRC, and Zambia) to push higher-tech manufacturing, and leveraging international institutions and FDI not only for capital but also for knowledge transfer and long-term capacity building .

Theoretical contribution lies in the introduction of a multilayer analytical framework that integrates TIS functions, PV design factors, and regional integration theory. This approach highlights how institutional dynamics and socio-technical drivers interact in shaping regional value chains. It adds nuance to the literature on regional industrialization in the Global South by linking demand creation, institutional orchestration, and capability building.

This thesis highly reliance on desk research with limited interviews, constrained access to region-wide data, and exclusion of sustainability aspects such as recycling and labor rights. Those served as a limitation for this thesis. The recommendations are preliminary and require feasibility studies at the country level to assess economic, social, and environmental viability .

In short, the study argues that SADC can transition from a fragmented, import-reliant solar PV market toward a competitive regional value chain by strategically leveraging its mineral resources, fostering coordinated regional action, and adapting lessons from China's developmental model.

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Appendix A. Factors scoring for Solar PV Value Chain

	Quartz mining	MG Silicon	SG Silicon	Ingot & Wafer	Cells	Module		Glass	Inverters	Plastic foils
Baseline requirements										
Existing industrial ecosystem	1	3	3	3	2	1		3	2	2
Domestic solar demand	1	2	2	1	3	3		1	2	2
Status of existing upstream PV actors	1	3	3	3	2	1		1	1	1
Infrastructure*	3	3	3	3	3	3		3	3	3
Raw material availability	3	2	1	1	1	1		3	1	1
Ease of doing business**	1	3	3	3	3	2		2	2	2
Key requirements for CAPEX-intensive steps										
Access to capital	3	3	3	2	2	1		2	1	1
Interest rate	3	3	3	2	2	1		2	1	1
Key requirements for OPEX-intensive steps										
Electricity cost	1	3	3	3	2	1		3	1	2
Electricity carbon intensity***	1	3	3	3	2	1		3	1	2
Labor cost	2	1	1	1	2	3		2	2	2
Key requirements for competence-intensive steps										
Qualified labor	2	3	3	3	3	1		2	2	2
R&D centers	1	2	2	2	3	2		1	1	1
IP availability	1	2	2	2	3	2		1	1	1

** Electricity, water, transport, ...*

*** See World Bank indicator: Ease of starting a business, ease of receiving building permit, juridical protection, taxes, currency, political stability, existence of trade agreements...*

**** Typically related to the presence of hydropower*

1: listed requirement is of **limited** importance for considered PV value chain step
2: listed requirement is of **medium** importance for considered PV value chain step
3: listed requirement is of **high** importance for considered PV value chain step

Legend:

source: Macé et al. (2023)

Appendix B. Interview Protocol

General Questions

1. Can I confirm your expertise, role, and organization again?
2. Do you confirm your consent to participate, as per the document I shared earlier?
3. Before we begin, do you have any questions for me?

Validation Questions: Involved Institutions & Its Role

1. Do you agree that these four institutions (regional institutions, country-level strategy, international institution, and FDI) play a central role in driving regional integration of the solar PV value chain in SADC?
2. Are there any other types of institutions or actors that you believe are equally or more important in this regionalization process?
3. How would you assess the role of your kind of institution in facilitating PV value chain integration in SADC region?

Validation & Exploration Questions: System Functions, Regional Integration, and Recommendations

1. What challenges that you think are hindering the PV value chain development?
2. How would you describe the current state of entrepreneurial activity in PV manufacturing (upstream/midstream) in SADC?
3. What are the main barriers to knowledge development and R&D in solar PV?
4. Are there active mechanisms for knowledge diffusion/exchange between your institutions and regional/national/actors in PV innovation in SADC region?
5. Do you believe that current policy direction and guidance of search is strong enough to support PV value chain integration, whether on Upstream, Midstream, or Downstream, or Acroos those segments?
6. Do you believe that current financial mechanisms (like donor programs, public-private partnerships, carbon tax, etc.) adequate to stimulate innovation in the PV value chain?
7. Do you believe that focusing on the market formation, especially in the downstream segment would lead to the innovation/development in the other two segments?
8. What do you think are the strategies that have been effective in building legitimacy and public support for local solar PV development?
9. Do you think all member countries/ all segments are moving in the same direction and same pace in advancing the PV sector development?
10. Final question would be: What recommendations would you make to better enable innovation and integration of the PV value chain in SADC?

Appendix C. Code Manager

Theme	Categories	Code	China	SADC
Value Chain Segments	Upstream	Auxiliary materials production/manufacturing	1	1
		Ingot and wafers production/manufacturing*	77	6
		Polysilicon production/manufacturing*	87	6
	Midstream	Capital equipment production/manufacturing	15	2
		Cells production/manufacturing*	108	8
		Modules manufacturing (assembly)*	93	14
	Downstream	Inverter production/manufacturing	2	3
		PV system installation & distribution*	185	90
F1. Entrepreneurial Activities	F1. Positive events	a. Actively doing export activities	5	0
		b. Companies entering market	18	11
		c. Growth of companies (IPO, efficiency)	17	0
		d. Self-sufficiency PV production	1	0
	F1. Negative events	e. Companies struggling/failing	7	1
		f. Dropped production rate	1	0
		g. Lack of supporting industries	0	2
F2. Knowledge Development	F2. Positive events	a. Demonstration and pilot projects	7	5
		b. Internal technological advancement	7	0
		c. Learning by doing/using	8	1
		d. R&D investment and expenditure	7	0
		e. Research and technological projects	6	4
	F2. Negative events	f. Failed pilot projects	0	1
		g. Lack of PV-focused research	0	1
		h. Product quality limitation	2	0
F3. Knowledge Exchange	F3. Positive events	a. International knowledge exchange	7	4
		b. Joint regional/national projects	4	3
		c. Exchange with high-tech sectors	2	0
		d. Knowledge/tech import	9	1
	F3. Negative events	e. Poor coordination among orgs	1	0
		f. Low tech imported/invested	0	1
F4. Guidance of Search	F4. Positive events	a. Clear regulation and policy	70	18
		b. Expert expectations	0	5
		c. Government targets	34	16
	F4. Negative events	d. Ineffective regulation	7	5
		e. Insufficient policy/regulation	0	2
		f. Misaligned tech priorities	5	2
		g. Negative expert opinions	0	1
F5. Market Formation	F5. Positive events	a. Domestic demand creation	7	2

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Theme	Categories	Code	China	SADC
		b. Overseas demand	8	0
		c. Projects installed	28	20
		d. Trade barriers removed	1	0
		e. Incentives and programmes	40	13
	F5. Negative events	f. Demand drop (crisis)	6	0
		g. Anti-dumping measures	8	0
		h. Small market size	4	3
		i. Slow domestic demand	2	5
F6. Resource Mobilization	F6. Positive events	a. Local gov. mobilisation	9	2
		b. Low labour/energy cost	1	0
		c. Public-private partnerships	0	3
		d. Financial support	37	18
		e. Skilled labour available	1	0
		f. Adequate infrastructure	0	1
	F6. Negative events	g. Lack of financial resources	0	0
		h. Skills/tech shortage	2	2
		i. Insufficient infrastructure	2	0
		j. Misallocated subsidies	9	1
F7. Creation of Legitimacy	F7. Positive events	a. Lobbying for PV	4	2
		b. Market standards proposed	5	2
		c. PV/RE promotion by gov/org	48	9
	F7. Negative events	d. Poorly implemented standards	0	3

*Indicates key PV manufacturing roles in the supply chain

Appendix D. Code Document Results

Table 2: Code-Document Result

Categories	Huang et al. (2016)	Guilhot (2022)	S. Zhang et al. (2014)	Y. Zhang et al. (2021)	Bai et al. (2024)	Baker and Sovacool (2017)	Jadhav et al. (2017)	Justo et al. (2022)	Kruger (2022)	Ndlovu (2025)
Driving Forces	54	22	54	58	30	11	32	5	11 8	
F1. Entrepreneurial Activities	21	7	9	5	8	3	4	2	4	2
F2. Knowledge Development	10	22	5	6	7	3	3	2	1	1
F3. Knowledge Exchange	10	0	0	4	7	3	0	0	4	2
F4. Guidance of Search	14	19	9	22	15	14	2	2	1	16
F5. Market Formation	12	9	16	8	12	5	2	0	1	1
F6. Resource Mobilization	16	7	10	12	6	10	0	0	5	1
F7. Creation of Legitimacy	22	25	9	16	21	35	15	5	16	4
Segments of Value Chain	12	8	9	14	18	8	10	6	9	7
Totals	**196**	**89**	**197**	**99**	**135**	**48**	**136**	**31**	**57**	**56**

Appendix E. Net Value and Normalized Value from PV TIS Assessment

.1. China's TIS Performance Assessment

Table 3: Innovation Activities Code Distribution Across Segments in Chinese Case

	Downstream	Midstream	Upstream
F1 - Negative Events	4	7	6
F1 - Positive Events	18	33	21
F2 - Negative Events	0	2	0
F2 - Positive Events	23	20	14
F3 - Negative Events	1	1	1
F3 - Positive Events	10	10	5
F4 - Negative Events	79	31	29
F4 - Positive Events	14	15	21
F5 - Negative Events	74	25	18
F5 - Positive Events	12	3	3
F6 - Negative Events	36	25	21
F6 - Positive Events	0	5	0
F7 - Negative Events	48	30	28

Table 4: Net Value of TIS Performance in Chinese Case

Functions/ Segments	**Downstream**	**Midstream**	**Upstream**
F1 - Entrepreneurial activities	14	26	15
F2 - Knowledge development	23	18	14
F3 - Knowledge exchange	13	9	5
F4 - Guidance of search	69	26	24
F5 - Market formation	56	12	7
F6 - Resource mobilization	24	22	18
F7 - Creation of legitimacy	48	30	28

Table 5: Normalized Value of TIS Performance in Chinese Case

Functions/ Segments	**Downstream**	**Midstream**	**Upstream**
F1 - Entrepreneurial activities	0,14	0,33	0,16
F2 - Knowledge development	0,28	0,20	0,14
F3 - Knowledge exchange	0,13	0,06	0,00
F4 - Guidance of search	1,00	0,33	0,30
F5 - Market formation	0,80	0,11	0,03
F6 - Resource mobilization	0,30	0,27	0,20
F7 - Creation of legitimacy	0,67	0,39	0,36

.2. SADC's TIS Performance Assessment

Table 6: Innovation Activities Code Distribution Across Segments in SADC's Case

	Downstream	Midstream	Upstream
F1 - Negative Events	3	2	1
F1 - Positive Events	10	2	0
F2 - Negative Events	2	1	1
F2 - Positive Events	10	1	1
F3 - Negative Events	0	1	0
F3 - Positive Events	8	1	0
F4 - Negative Events	8	4	1
F4 - Positive Events	34	2	1
F5 - Negative Events	8	2	0
F5 - Positive Events	31	2	1
F6 - Negative Events	3	2	2
F6 - Positive Events	22	1	1
F7 - Negative Events	2	2	0
F7 - Positive Events	12	2	1

Table 7: Net Value of TIS Performance in SADC's Case

Functions/ Segments	**Downstream**	**Midstream**	**Upstream**
F1 - Entrepreneurial activities	7	0*	-1**
F2 - Knowledge development	8	0	0
F3 - Knowledge exchange	8	0	0
F4 - Guidance of search	26	-2	0
F5 - Market formation	23	0	1
F6 - Resource mobilization	19	-1	-1
F7 - Creation of legitimacy	10	0	1

*(0) as neutral nuance, meaning that there is an indication that the innovation functions are present but not strong enough to support the development of PV within the segment.
**The negative values indicates that activities that negatively contribute to technological change were mentioned more frequently than the positive ones. This suggests that certain functions are poorly fulfilled, which may pose barriers to the development of the solar PV value chain.

Table 8: Normalized Value of TIS Performance in SADC's case

Functions/ Segments	**Downstream**	**Midstream**	**Upstream**
F1 - Entrepreneurial activities	0,32	0,07	0,04
F2 - Knowledge development	0,36	0,07	0,07
F3 - Knowledge exchange	0,36	0,07	0,07
F4 - Guidance of search	1,00	0,00	0,07
F5 - Market formation	0,89	0,07	0,11
F6 - Resource mobilization	0,75	0,04	0,04
F7 - Creation of legitimacy	0,43	0,07	0,11

Appendix F. National Government Bodies and Its Role in SADC

Country	National Government Bodies	Role in PV Development
Angola	Ministry of Energy and Water (Ministério da Energia e Águas, MINEA)	Responsible for policy planning and development; National Focal Institution for SACREEE
	Programme for Rural Electrification of Rural Areas (PNER)	Has the mandate to drive rural electrification
	Instituto Regulador do Sector Eléctrico (IRSE)	Affiliated to the Regional Energy Regulators Association and member of SAPP
	Savings and Credit Bank (BPC); Development Bank of Angola (BDA); Banco Sol	Member of DFI network to financing development agenda and advancing productive capacity
Botswana	Ministry of Mineral Resources, Green Technology and Energy Security (MMGE)	Responsible for policy development and planning for the energy sector; National Focal Institution for SACREEE
	Botswana Energy Regulatory Authority	Affiliated to the Regional Energy Regulators Association
	Botswana Development Corporation (BDC)	Member of DFI network to financing development agenda and advancing productive capacity
Comoros	The Ministry of Energy, Water, and Hydrocarbons (Ministère de l'Energie de l'Eau et des Hydrocarbures – MEEH)	Oversees the energy sector; National Focal Institution for SACREEE
DRC	Ministry of Energy and Hydraulic Resources(Ministre de l'Energie et de l'Hydraulique)	Responsibility for coordinating the development and management of the energy sector; National Focal Institution for SACREEE
	National Rural and Peri-urban Electrification and Energy Services Agency (ANSER)	In charge of rural electrification
	Societe Financiere de Developpment (SOFIDE); Fonds de Promotion de l'Industrie (FPI)	Member of DFI network to financing development agenda and advancing productive capacity
Eswatini	Ministry of Natural Resources and Energy	Oversees policy development and implementation
	Eswatini Energy Regulatory Authority (EERA)	Affiliated to the Regional Energy Regulators Association; National Focal Institution for SACREEE
	Ministry of Commerce, Trade and Industry	The custodian of the country's industrialisation policies and strategies

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Country	National Government Bodies	Role in PV Development
	Eswatini Development and Savings Bank; Eswatini Development Finance Corporation; Industrial Development Company of Eswatini; National Industrial Development Corporation of Eswatini	Member of DFI network to financing development agenda and advancing productive capacity
Lesotho	Ministry of Energy and Meteorology (MEM)	Responsible for energy policy planning, development and implementation of projects
	Lesotho Electricity and Water Authority (LEWA)	Affiliated to the Regional Energy Regulators Association
	Basotho Enterprise Development Corporation (BEDCO); Lesotho National Development Corporation (LNDC)	Member of DFI network to financing development agenda and advancing productive capacity
Madagascar	Ministère de l'Eau, de l'Energie et des Hydrocarbures, (MEEH)	Responsible for the national energy policy and coordination of the activities in the energy sector
	Direction de l'Electricite et des Energies Renouvelables (DEER)	Implements the policy in the electricity and renewable energy domain
	Societe Nationale de Participations (SONAPAR)	Member of DFI network to financing development agenda and advancing productive capacity
Malawi	Ministry of Energy	Responsible for the national energy policy and coordination of the activities in the energy sector
	Malawi Energy Regulatory Authority (MERA)	Responsible for regulating the energy sector to ensure fairness, transparency, efficiency and cost effectiveness for the benefit of the consumers and operators; affiliated to the Regional Energy Regulators Assoiation
	Malawi Rural Electrification Programme (MAREP)	initiative Increase access to electricity in rural areas
	Ministry of Trade Industry and Tourism (MITT)	Lead institution for coordinating the design, implementation and monitoring the National Industrial policy in Malawi
	Export Development Fund (EDF)	Member of DFI network to financing development agenda and advancing productive capacity
Mauritius	The Ministry of Energy and Public Utilities	Monopolizes the transmission, distribution, and sale of electricity in Mauritius; National Focal Institution for SACREEE
	Central Electricity Board (CEB)	Responsible for the electricity sector planning
	Mauritius Renewable Energy Agency (MARENA)	Responsible for the promotion of renewable energy technologies
	Utility Regulatory Authority	Affiliated to the Regional Energy Regulators Assoiation

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Country	National Government Bodies	Role in PV Development
	Ministry of Industry , Commerce and Consumer Protection	Act as a facilitator and catalyst for the development of a resilient, vibrant and competitive manufacturing sector with a view to fostering employment creation and creating wealth for higher economic growth
	Development Bank of Mauritius (DBM)	Member of DFI network to financing development agenda and advancing productive capacity
Mozambique	Ministério dos Recursos Minerais e Energia	Responsible for the national energy policy and coordination of the activities in the energy sector
	Autoridade Reguladora de Energia (ARENE)	Mozambique Affiliated to the Regional Energy Regulators Assoiation
	PROLER Programme	Support the Mozambican government's in their bids for renewable energy power generation projects-tenders (solar and wind)
	Rural electrification programmes	Implemented by EDM to accelerate energy access and address the challenge of energy poverty
	Gapi-Sociedade de Investimentos (Gapi-SI); Banco Nacional de Investimento (BNI)	Member of DFI network to financing development agenda and advancing productive capacity
Namibia	Ministry of Mines and Energy (MME)	Responsible for the national energy policy and coordination of the activities in the energy sector
	Regional Electricity Distributors (REDs)	Responsible for supplying electricity to the residents in specific regions in Namibia
	Electricity Control Board (ECB)	Affiliated to the Regional Energy Regulators Assoiation
	Namibia Energy Institute (NEI)	National Focal Institution for SACREEE
	Modified Single Buyer Model (MSB)	Increase the participation of the private sector in the energy sector
	Ministry of Trade and Industry	Takes full responsibility for formulating policy on and directing Namibia's industrialization
	Environmental Investment Fund of Namibia (EIF); Development Bank of Namibia (DBN)	Member of DFI network to financing development agenda and advancing productive capacity
Seychelles	Ministry of Environment, Energy and Climate Change (MEECC)	Responsible for policy planning in Seychelles
	Seychelles Energy Commission (SEC)	Regulates sector activities; National Focal Institution for SACREEE
	Development Bank of Seychelles (DBS)	Member of DFI network to financing development agenda and advancing productive capacity
South Africa	Department of Mineral Resources and Energy (DMRE)	In charge of policy development and planning
	National Energy Regulator of South Africa (NERSA)	Affiliated to the Regional Energy Regulators Association

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Country	National Government Bodies	Role in PV Development
	Independent Power Producer Procurement Office	Responsible for the national procurement and coordination of renewable energy capacity in South Africa
	Department of Trade and Industry (DTI)	Home for the country's industrialization initiatives, which plays the coordination, regulation, and policymaking roles
	Industrial Development Corporation (IDC)	Member of DFI network to financing development agenda and advancing productive capacity
Tanzania	Ministry of Energy	Responsible for policy planning and development
	Rural Energy Agency (REA)	Has a mandate to promote and facilitate availability and access to modern energy services in rural mainland Tanzania
	Energy and Water Utilities Regulatory Authority (EWURA)	Regulates the Electricity Supply Industry
	Ministry of Industry and Trade	Manage 5 units of department in formulating country's industrial policy cycle work closely with the private sector in the implementation of the policy/strategy, while obtain support in the monitoring and evaluation stage from the research institutes and statistics agency
	National Development Corporation (NDC); TIB Development Bank (TIB)	Member of DFI network to financing development agenda and advancing productive capacity
Zambia	Ministry of Energy	Responsible for the development and management of energy resources including policy development and administration
	Rural Electrification Authority of Zambia (REA)	Has a mandate to provide electricity infrastructure to all rural areas
	Energy Regulatory Board (ERB)	Responsible for developing, managing and implementing sector regulation; National Focal Institution for SACREEE
	Ministry of Commerce Trade and Industry (MCTI)	Head institution for developing industrial polices and strategies
	Development Bank of Zambia (DBZ)	Member of DFI network to financing development agenda and advancing productive capacity
Zimbabwe	Ministry of Energy and Power Development (MEPD)	National Focal Institution for SACREEE
	Zimbabwe Energy Regulatory Authority (ZERA)	Affiliated to the Regional Energy Regulators Assoiation
	Rural Electrification Agency (REA)	Ensure universal access to energy by rural communities by 2030

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Country	National Government Bodies	Role in PV Development
	Industrial Development Corporation of Zimbabwe Limited (IDCZ); Infrastructure Development Bank of Zimbabwe (IDBZ) (formerly Zimbabwe Development Bank); Small and Medium Enterprises Development Corporation (SMEDCO)	Member of DFI network to financing development agenda and advancing productive capacity

Source: Author's own compilation based on data gathered from https://www.sacreee.org, https://www.sadc-dfrc.org, and SADC (2021c)

Appendix G. PV Companies Distribution in SADC

Company	Country	Auxiliary Manufacturer	Ingots Manufacturer	Wafers Manufacturer	Cells Manufacturer	Module/Panel Manufacturer	Machinery / Production Equipment	PV Component Manufacturer
Engineering Centre	Namibia							✓
Energy Solutions Seychelles	Seychelles							✓
Aberdare Cables	South Africa							✓
Actom	South Africa							✓
Allbro	South Africa							✓
Alvern Cables	South Africa							✓
Apex	South Africa							✓
Ario	South Africa							✓
ARTsolar (Pty) Ltd	South Africa				✓	✓		
Axe Struct	South Africa							✓
Balancell	South Africa							✓
BlueNova	South Africa				✓	✓		
Bushveld Energy	South Africa							✓
Caracal Engineering	South Africa							✓
Centurion Systems	South Africa				✓	✓		
Chadha Power (SA)	South Africa							✓
Clotan Steel	South Africa							✓
CTG EYIL	South Africa							✓
Deltec Energy Solutions	South Africa							✓
Deo Solar	South Africa							✓
Ener-G-Africa Holdings Ltd	South Africa				✓	✓		
Energria	South Africa							✓
EnerSol Africa	South Africa				✓	✓		
Enertec Batteries	South Africa							✓
EzyLight	South Africa				✓			
FNB	South Africa							✓

Freedom Won	South Africa			✓
GPT Renewables Pty Ltd	South Africa			✓
Granville	South Africa			✓
Greenrich	South Africa			✓
Hanchu Energy	South Africa			✓
HRP	South Africa			✓
Hubble Energy	South Africa			✓
Hulamin	South Africa			✓
iG3N (Pty) Ltd	South Africa			✓
Ilaanga Energy	South Africa			✓
Iseli Energy	South Africa	✓		
Jsdsolar SA	South Africa			✓
Katbatt	South Africa			✓
KD Solar	South Africa	✓	✓	
LBSA	South Africa			✓
Lumax Energy	South Africa			✓
Magneto Energy	South Africa			✓
Metalforming Technology SA	South Africa	✓		
Microcare	South Africa			✓
MLT Inverters	South Africa			✓
NeOn Energy (Pty) Ltd	South Africa			✓
Netshield (Pty) Ltd	South Africa	✓		
PiA Solar	South Africa			✓
Pratley	South Africa			✓
Red Pole Energy	South Africa			✓
Reliable Transformers	South Africa			✓
Repro Suppliers PTY (Ltd)	South Africa	✓		
Reutech Radar Systems	South Africa			✓
Revive	South Africa			✓
REVOV	South Africa			✓
Sable Energy	South Africa			✓
Salvare Solar	South Africa			✓
Sinetech Solar	South Africa	✓	✓	
Solar MD	South Africa			✓
Solar Structures Africa	South Africa			✓
Solarframe	South Africa			✓
Steropsolar	South Africa			✓

SunFix	South Africa							✓
Swagefast	South Africa							✓
Synapse	South Africa							✓
Tristar Electrical	South Africa							✓
Trojan Battery Company	South Africa							✓
TTS Africa	South Africa							✓
Upowa	South Africa							✓
UVSS	South Africa							✓
Valsa Trading (Pty)	South Africa				✓	✓		
WEST	South Africa							✓
ZEPHYR SOLAR TECHNOLOGIES	South Africa							✓
National Luna	South Africa							✓
Metalforming Technology	South Africa						✓	
Gold Star Battery	Tanzania							✓
Astanah Energy	Zambia							✓
Amount of Companies		0	0	0	0	13	1	72