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Review Article

Solar Technology Penetration in Sub-Saharan Africa: Status, Drivers, Barriers, and Future Prospects

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ABSTRACT

Sub-Saharan Africa's severe energy access deficit hinders its socio-economic development, affecting millions. This review is motivated by the need to understand the factors influencing the adoption of solar technology as a potential solution. It is hypothesized that while solar technology offers a viable path to electrification, its penetration is significantly influenced by a complex interplay of drivers and barriers. A systematic review of academic and grey literature was conducted to assess the current status, drivers, and barriers of solar technology penetration. Beyond synthesizing academic and grey literature, a structured Strength, Weaknesses, Opportunities and Threats analysis was conducted, followed by a pairwise comparison matrix and Analytic Hierarchy Process. The analysis reveals that financing barriers, weak grid infrastructure, and policy instability are the most important obstacles, while abundant solar resources, declining technology costs, and innovative business models act as major drivers. The Strength, Weaknesses, Opportunities, Threats–Analytic Hierarchy Process framework identifies and ranks strategic factors, generating actionable solution strategies such as blended finance, regulatory stability, and regional quality assurance mechanisms.

KEYWORDS

Solar energy; Sub Saharan Africa; Status; Drivers; Opportunities; Barriers.

1. INTRODUCTION

Sub-Saharan Africa (SSA) faces increasing energy access challenge, representing a major hurdle to development. Despite abundant energy resources, the region significantly lags in providing modern energy services [1]. As of 2022, approximately 600 million people in Africa,

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predominantly in SSA, lacked electricity access [2], accounting for 43% of the continent's population [2] and 83% of the global deficit [3]. The overall electrification rate in SSA was only 51.5% in 2022 [4]. Recent trends are concerning, the number of people globally without electricity access increased in 2022 for the first time in over a decade, driven primarily by SSA, where the unelectrified population (571.1 million) surpassed 2010 levels [5]. Population growth is outpacing new connections, exacerbated by global crises and climate impacts [6]. This underscores the need for rapid, scalable solutions, as traditional grid extension is often too slow and costly [7], [8]. The deficit is most severe in rural areas, home to over 80% of the unelectrified [2], with stark urban-rural divides (e.g., 78% urban vs. 28% rural access in 2020 [7], [9]). Nigeria, Democratic Republic of the Congo (DRC), and Ethiopia alone account for nearly a third of the global access deficit [3]. This lack of energy constrains economic activity, public services, technology adoption, and quality of life [10], while energy demand is projected to surge due to population growth and economic aspirations [11]. Table 1 and Figure 1 provide an overview of population and electricity access trends in SSA.

Table 1. Population and Electricity Access Trends in SSA

Year	**Population (Millions)**	**Population without electricity access (Millions)**	**Population annual % change**	**Electricity access rate (%)**
2000	681.13	506	2.69	25.70
2001	699.59	513	2.71	26.16
2002	718.66	520	2.73	27.34
2003	738.32	529	2.73	29.59
2004	758.65	538	2.75	29.37
2005	779.67	547	2.77	29.35
2006	801.27	556	2.77	31.20
2007	823.56	564	2.78	32.52
2008	846.66	569	2.80	32.40
2009	870.35	577	2.80	32.63
2010	894.67	588	2.79	33.34
2011	919.53	594	2.78	35.90
2012	944.97	604	2.77	36.78
2013	971.23	612	2.78	38.03
2014	997.96	601	2.75	38.35
2015	1025.25	594	2.73	39.20
2016	1052.82	584	2.69	43.83
2017	1080.94	572	2.67	43.76
2018	1110.00	572	2.69	46.42
2019	1139.32	571	2.64	47.20
2020	1169.02	581	2.61	48.55
2021	1199.01	597	2.57	50.66
2022	1229.21	600	2.52	51.59
2023	1259.90	601	2.50	53.26

***Sources:** *International Energy Agency (IEA). Global population without access to electricity by region, 2000-2021 Macrotrend.net. SSA Population (1950-2025), Macrotrend.net. SSA Electricity Access (2025)*

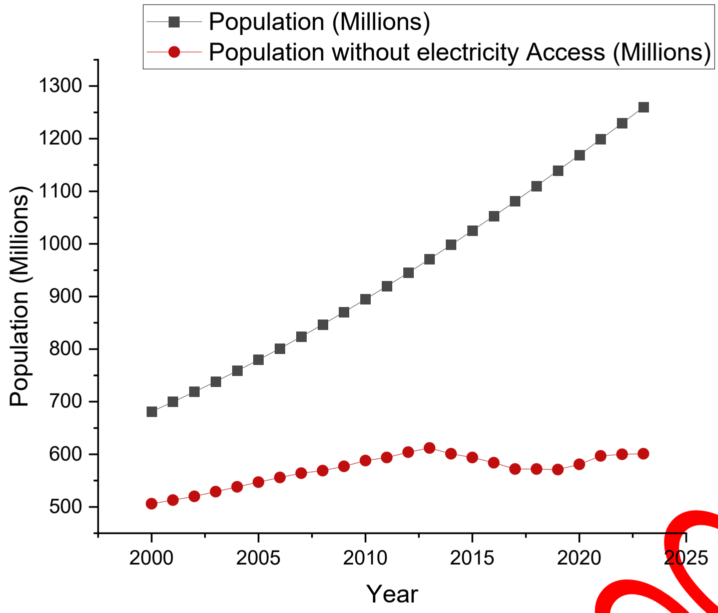

Figure 1: Total Population and Population without electricity access in SSA (2000–2023)

An examination of the provided data, presented in Table 1 and Figure 1 reveals a dynamic and complex picture of population growth and electricity access in SSA from the year 2000 to 2023. While the region has made significant strides in increasing the percentage of its population with access to electricity, the rapid pace of population growth has posed a persistent challenge, leaving a large number of people without this essential service. Figure 1 clearly indicates a steep and consistent rise in the total population of SSA over the 24-year period. The population grew from 681.13 million in 2000 to 1259.90 million in 2023, an increase of approximately 85%. This translates to a high average annual growth rate, fluctuating between 2.50% and 2.80% throughout the period. This sustained high population growth is a key factor influencing the region's development landscape, including the challenge of providing universal electricity access.

There is a clear and positive trend in the electricity access rate, which has more than doubled from 25.70% in 2000 to 53.26% in 2023. This demonstrates substantial and consistent efforts by countries in the region to expand their electricity grids and implement off-grid solutions. The annual increase in access has been steady, contributing to a significant overall improvement over the two decades. This progress underscores the commitment to achieving Sustainable Development Goal 7 (SDG7), which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Despite the commendable increase in the electricity access rate, the absolute number of people without electricity has remained stubbornly high and has even seen periods of increase. The number of people without access began at 506 million in 2000 and, after an initial period of increase, peaked at 612 million in 2013. Since then, the numbers have shown a slight, fluctuating decline, ending at 601 million in 2023.

The implication arising from Table 1 and Figure 1 is that population growth is significantly outpacing electrification efforts. This creates an "electrification treadmill" effect; even with new connections, the sheer volume of new births means that the absolute number of unelectrified people struggles to decrease significantly. This dynamic exacerbates the energy access deficit, making it not just persistent but potentially more entrenched for a larger absolute number of people. The data from Table 1 strongly supports the need for rapid, scalable solutions, as traditional grid extension is often too slow and costly. The positive impact of solar home systems (SHS) growth in 2023 underscores the strategic importance of decentralized, off-grid solar solutions in reaching the rapidly expanding and predominantly rural unelectrified population, where over 80% of the deficit is concentrated [12]. The unlikelihood of meetingSDG7 by 2030 at the current pace further highlights a significant gap in policy effectiveness, investment levels, and implementation strategies, reinforcing the observation that current investment is far below the estimated USD 20-50 billion needed annually for SDG7 [13]. Amidst this, solar energy offers transformative potential, SSA boasts 60% of the world's best solar resources [2], with high irradiation levels [14], yet hosts only ~1% of global installed solar PV capacity [6]. The dramatic fall in solar PV costs (82% decrease 2010-2019 [15]) makes it the cheapest new electricity source in many parts of Africa, projected to outcompete all others by 2030 [2]. Solar provides a pathway to SDG7 [13], supports climate goals under the Paris Agreement and nationally determined contributions (NDCs) [16], and allows SSA to leapfrog fossil-fuel-intensive development [17].

The primary objectives of this review are to: (1) Systematically assess the current penetration levels of diverse solar technologies (utility-scale, rooftop, SHS, mini-grids, solar thermal) across SSA; (2) Analyze the multi-faceted drivers (economic, policy, social) accelerating solar adoption and the persistent barriers (financial, regulatory, infrastructural, market-related) hindering it; (3) Evaluate the efficacy of existing policy frameworks and innovative business models in promoting solar deployment; and (4) Identify key strategic priorities and actionable recommendations to unlock SSA's vast solar potential and achieve sustainable energy goals.

2. MATERIALS AND METHODS

To ensure the comprehensiveness, transparency, and academic rigor of this review, a systematic methodology was employed for literature selection, data sourcing, and analytical synthesis. This approach addresses the need for a systematic methodology description for literature selection and review scope, as well as the need for proper evaluation of data sources and methods.

2.1. Literature selection and review scope

The systematic literature review methodology involved a structured search, screening, and selection process designed to minimize potential bias and ensure comprehensive coverage of relevant scholarship and authoritative reports. The search strategy utilized a combination of academic databases and key institutional repositories for grey literature. Academic databases included Scopus, Web of Science, and Google Scholar, while institutional repositories comprised World Bank Open Knowledge, International Renewable Energy Agency (IRENA) publications, IEA reports, International Monetary Fund (IMF), African Development Bank (AfDB) documents, Energy Sector Management Assistance Program (ESMAP) technical reports, DNV reports, and National Renewable Energy Laboratory (NREL) publications. The primary keywords and search strings used included: "solar energy SSA," "renewable energy access Africa," "mini-grids SSA," "solar home systems Africa," "energy policy SSA," "solar finance Africa," "energy transition Africa," and "electricity access trends Africa." Boolean operators (AND, OR) and date filters were applied to refine searches and prioritize recent publications.

The inclusion criteria stipulated that only peer-reviewed journal articles, authoritative reports, and datasets from reputable international organizations, along with relevant grey literature were considered. Emphasis was placed on incorporating the latest studies published post-2020 to ensure cutting-edge relevance and reflect the most current understanding of the subject. Included studies had to directly address solar technology penetration, its drivers, barriers, innovations, policy, and governance specifically within the SSA context. Exclusion criteria involved the removal of studies not directly relevant to SSA, outdated information (unless specifically used for historical trend analysis), or non-English language publications. The review scope is designed to be comprehensive, encompassing all major solar technologies. This includes Solar Photovoltaic (PV) across utility-scale, rooftop, and decentralized applications (such as SHS and mini-grids), as well as solar thermal applications (e.g., solar water heaters). The analysis examines both off-grid and grid-tied solar applications and their interplay with energy storage solutions. Geographically, the analysis covers the broad SSA region, while acknowledging and highlighting significant country-specific nuances and successful case studies to provide a comprehensive yet context-sensitive perspective.

2.2 SWOT analysis

SWOT factors were identified through a systematic review of 100+ peer-reviewed articles, authoritative reports, and regional case studies. Factors were shortlisted based on recurrence, policy relevance, and stakeholder significance. Expert consultation was conducted with three energy researchers to validate and refine the factors. To prioritize factors, the Analytic Hierarchy Process (AHP) was applied. A pairwise comparison matrix was developed using the Saaty 1–9 scale, comparing the relative importance of Strengths vs. Weaknesses, Opportunities vs. Threats, and their cross-interactions. Consistency ratios (CR) were calculated to ensure reliability (<0.1 threshold). Weighted scores were derived to rank factors, identifying those most influential in shaping strategic solar adoption pathways.

3. OVERVIEW OF SOLAR TECHNOLOGIES AND CURRENT STATUS

This section provides a foundational overview of the primary solar photovoltaic (PV) technologies being deployed to address the energy deficit in SSA. Solar PV technology is highly versatile and can be implemented across various scales, from large, centralized power plants to small, decentralized systems serving individual households. To understand the landscape of solar energy in the region, it is crucial to distinguish between three main categories: utility-scale solar farms that feed into the national grid, community-level mini-grids, and standalone off-grid systems such as SHS and pico-solar products. The following subsections will explore the characteristics of each of these technological applications and assess their current deployment status and contribution to energy access across the continent.

3.1. Definitions

To ensure clarity and precision throughout this review, "solar technology penetration" is defined in a multi-faceted manner, encompassing various dimensions of adoption and integration within the energy landscape of SSA. This definition addresses the need for a precise understanding of the term, moving beyond a simplistic interpretation. In this context, solar technology penetration refers to the extent to which solar energy solutions have been adopted, integrated, and are actively contributing to the energy mix and socio-economic development across SSA [18]. This encompasses several key dimensions:

Installed capacity refers to the total generating capacity of solar PV systems (including utility-scale plants, rooftop installations, and decentralized mini-grids) and solar thermal systems (such as solar water heaters) that have been successfully deployed within the region [19]. This is typically measured in Megawatts (MW) or Gigawatts (GW) and provides a quantitative measure of the physical presence of solar infrastructure. Adoption rate quantifies the uptake of solar technologies by end-users [20]. It can be expressed as the percentage or absolute number of households, businesses, or communities that are actively utilizing solar technologies for their energy needs [21]. Metrics often include the number of SHS sold or the number of new connections to solar-powered mini-grids [21]. Market share indicates the proportion of solar energy within the overall electricity generation mix or among new energy connections, relative to other energy sources such as fossil fuels, hydropower, or traditional biomass [22]. A growing market share signifies Solar's increasing prominence in the energy landscape. Geographic spread assesses the distribution and reach of solar technology adoption across different demographic settings, including urban, peri-urban, and remote rural areas [23]. It highlights regional disparities and the extent to which last-mile electrification challenges are being addressed by solar solutions. Depth of access/tier of service evaluates the capacity of solar solutions to enable higher tiers of energy service [24]. This includes providing sufficient power for productive uses (e.g., agricultural irrigation, small and medium enterprises), industrial applications, and essential community services (e.g., health clinics, schools), thereby indicating a more transformative and sustainable impact on livelihoods and economic development [25]. Various solar technologies are deployed across SSA, tailored to different contexts as outlined in the following section.

3.2 Solar photovoltaic

Solar PV, which converts sunlight directly into electricity, is the most prominent solar technology in SSA's energy transition narrative, driven by its falling costs and modularity [7]. It manifests in several forms:

- Large grid-connected plants in SSA have vast potential, but deployment lags. Competitive auctions are lowering prices; potential exists to replace fossil fuel plants with solar power plants [6].
- Rooftop Solar: Increasingly adopted by residential and especially commercial & Industrial (C&I) users, driven by cost savings and the need for reliable power amidst grid outages, supportive policies like net metering help [26].
- SHS: Small, standalone systems providing basic Tier 1-2 access (lighting, charging) [27] to millions off-grid, enabled by PayGo financing [28]. SHS sales surged recently, particularly in West Africa, as of 2023, SHS provided primary access for 43 million people in SSA and backup for another 30 million [29].

3.3 Solar thermal

Solar thermal technologies utilize sunlight to generate heat rather than electricity. While SSA has potential for these applications [28], they receive less attention in current electrification discourse compared to PV. Solar water heaters are relatively common in specific markets like South Africa, driven by incentive programs and building regulations [30]. However, other applications like solar cookers have faced significant adoption challenges and are often deemed insufficient solutions on their own [28]. The available data suggests a lower overall deployment and focus of solar thermal compared to PV technologies for electricity generation [31].

3.4 Off-grid solutions

Important for rural electrification where grid extension is costly; Standalone systems: This category is dominated by the SHS described earlier. They represent the most viable and least-cost option for reaching a significant portion of the currently unelectrified population, particularly in remote locations [11]. The PayGo business model has been revolutionary, enabling households to lease systems via mobile money payments [14]. Mini-grids: These are independent electrical distribution networks serving a localized group of customers, such as a village, community, or commercial cluster [32]. Typically defined as having a capacity below 10 MW [33], mini-grids in SSA are increasingly powered by solar PV, often incorporating battery storage to ensure continuous supply [7]. Hybrid systems, combining solar PV with diesel generators or other sources, are also common to enhance reliability [7]. Mini-grids are considered essential for powering productive uses (e.g., grain milling, irrigation, small businesses) that require more energy than basic SHS can provide [34]. They offer a higher tier of energy service and can sometimes be designed for future integration with the main grid [35]. Projections suggest mini-grids could serve hundreds of millions of Africans by 2030-2040 if deployment accelerates significantly [33]. Table 2 and Figure 2 present mini-grid deployment trends in SSA, highlighting the current status of this technology penetration in the region. Current deployment stands at around 3,000 operational mini-grids, a substantial increase from

~500 in 2010, with another 9,000 planned, but this falls far short of the estimated 160,000+ needed to meet access goals by 2030 [9].

Table 2. Mini-grid deployment trends in SSA

Timeframe	**Installed Mini-Grids (Approx.)**	**Planned Mini-Grids (Approx.)**	**People Connected (Approx. Millions)**	**Investment (Approx. USD Billions)**	**Key Observations**	**Source**
2010	~500	-	-	-	Baseline	[36]
~2022/2023	>3,000 (Installed globally: >21,000)	~9,000 (Planned globally: ~29,400)	~11 (Global: 48)	~$9 (Global: 29)	Significant growth, but SSA lags Asia in installed base. Most planned are in Africa.	[35]
2023	173 (Commissioned)	215 (Agreements signed)	>0.1 (Connections)	-	Example of market-driven program success.	[37]
2030 (Target for Universal Access)	>160,000 - 217,000	-	380 - 490	$91 - $127	Massive scale-up needed from current pace.	[38]
2030 (Projected at Current Pace)	~12,000 (New additions)	-	~46	~$9	Current pace insufficient for targets.	[38]

Note: Figures represent estimates from various reports and may include different definitions or timeframes. Global figures provided for context where available.

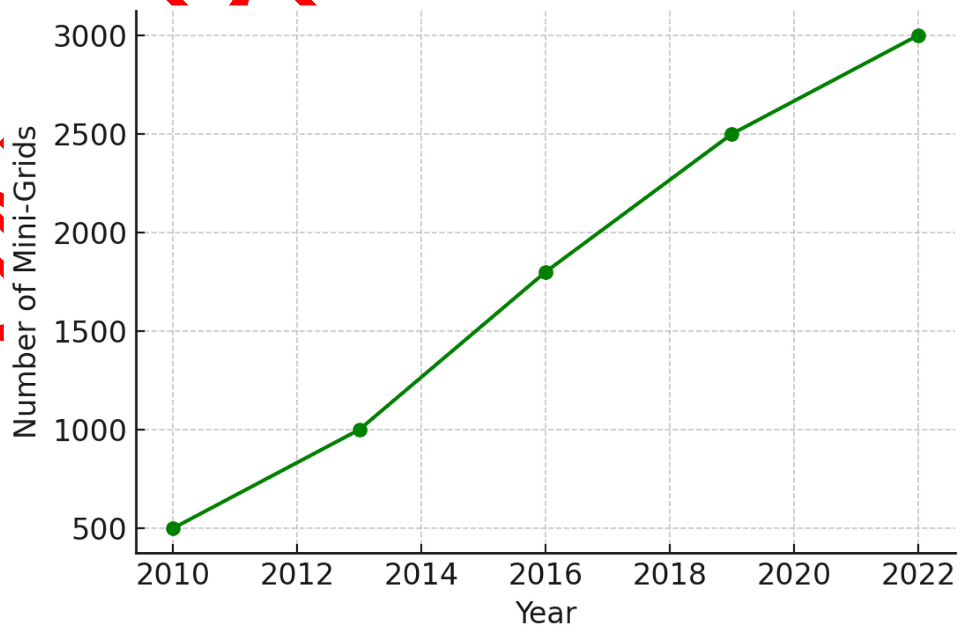

Figure 2: Growth of Operational Mini-Grids in SSA (2010–2022)

Table 2 further emphasizes the substantial gap between current mini-grid deployment and the scale required to achieve universal energy access by 2030. While there has been significant growth in the number of installed mini-grids, the current pace of deployment is clearly insufficient to meet the ambitious targets, underscoring the need for accelerated efforts and increased investment.

3.5 Grid-tied systems

This category includes any solar system connected to the main utility grid, encompassing utility-scale plants and net-metered rooftop installations [39]. While offering the potential for large-scale clean energy injection, grid-tied solar faces significant challenges in SSA related to the existing grid infrastructure [40]. Many national grids are weak, unstable, and suffer from limited reach and capacity, making it difficult to integrate large amounts of variable renewable energy like solar [9]. Poor performance and financial instability of national utilities further complicate grid integration and management [9]. Improvements to transmission and distribution infrastructure are therefore imperative prerequisites for scaling up grid-tied solar.

3.6 Energy storage

Energy storage systems are necessary for managing solar intermittency, especially for off-grid reliability [41]. Lead-acid batteries dominate installed mini-grids (~66%), but lithium-ion (~32%) is gaining share due to better performance [7]; falling battery costs are key enablers [9]. Table 3 presents solar PV and battery cost reduction trend in different years.

Table 3: Solar PV and Battery Cost Reduction Trends (Global Weighted Average LCOE)

Technology	**2010 Cost (USD/kWh)**	**2020 Cost (USD/kWh)**	**2022 Cost (USD/kWh)**	**2023 Cost (USD/kWh)**	**% Decrease (2010-2023 Approx.)**	**Source**
Utility-Scale Solar PV	~$0.40 - $0.417	~$0.057	$0.048	$0.044	~89	[16]
Onshore Wind	~$0.089	~$0.039	-	$0.033	~63	[16]
Offshore Wind	~$0.188	~$0.084	-	~$0.081	~57	[42]
Concentrating Solar Power (CSP)	$0.39	~$0.108	-	<$0.12	~70	[43]
Battery Storage (System Cost)	-	-	-	-	85-89	[42]

Note: LCOE (Levelized Cost of Electricity) represents the average minimum price electricity must be sold at to offset production costs over the plant's lifetime. Costs are global weighted averages and can vary significantly by region and project specifics. Battery cost reduction refers to overall system/pack costs, not LCOE.

The dramatic global cost reductions experienced by solar PV and battery storage technologies is illustrated in Table 3. The approximate 89% decrease in the (LCOE) for utility-scale solar PV from 2010 to 2023 is particularly significant. This drastic reduction fundamentally alters the economic viability of solar projects in SSA, making them increasingly competitive with traditional energy sources. The substantial decrease in battery storage system costs (85-89%) further enhances the attractiveness of solar solutions by addressing intermittency challenges, thereby making solar a more reliable and dispatchable power source.

3.7 Recent innovations in solar technology adoption specific to SSA

Recent years have witnessed significant innovations in solar technology and its adoption models, particularly tailored to the unique challenges and opportunities within SSA [44]. These advancements are important for accelerating penetration beyond basic access. One area of innovation lies in the core solar technologies themselves. There have been continuous improvements in PV panel efficiency, allowing more electricity generation from smaller footprints, and advancements in battery energy density, which enhances the storage capacity and reliability of solar systems [16]. Beyond hardware, significant innovations have emerged in enabling technologies and system integration.

The integration of smart grid technologies and digitalization for remote monitoring and payment systems is transforming solar energy management in SSA [45]. Artificial Intelligence (AI) and the Internet of Things (IoT), collectively known as AIoT, are being applied to improve solar energy monitoring and control [46]. IoT-enabled monitoring devices facilitate real-time detection of issues, enhancing the overall reliability and effectiveness of solar energy systems. AI algorithms analyze real-time and historical data to improve energy forecasting, optimize panel orientation, and proactively schedule maintenance, thereby reducing operational costs and improving efficiency [47].

While still nascent, projects are exploring grid-scale battery energy storage systems (BESS) to dramatically speed up and deepen the penetration of renewable energy, as seen in South Africa's initiatives to install almost 360 MW of large-scale energy storage infrastructure at six Eskom substation sites [48]. Hybrid systems, combining solar PV with other energy sources, are becoming more prevalent to enhance reliability and address intermittency [49]. Beyond common solar-diesel hybrids, more advanced configurations are emerging, such as floating solar PV combined with hydropower [50]. This approach leverages existing hydropower infrastructure and reservoirs for solar deployment, optimizing land use and potentially reducing evaporation, while providing a stable backup to intermittent solar power [51].

New financing models have been particularly transformative for solar adoption in SSA, Pay-as-you-go (PayGo) financing model, using widespread mobile money platforms, has been revolutionary for the SHS market [52]. PayGo breaks down the prohibitive upfront cost barrier, enabling millions of low-income households to access basic solar energy services by making small, regular payments via mobile phone [53]. This innovation has significantly expanded access to basic electrification in remote and underserved areas. While PayGo addresses consumer affordability for small systems, larger infrastructure projects like mini-grids and utility-scale plants require different financing structures [54]. There is a growing emphasis on blended finance, which strategically uses public or concessional funds to de-risk projects and crowd in private capital [55]. Initiatives like Nigeria's National Electrification Project (NEP) exemplify a market-driven approach, providing grants to foster private sector participation in mini-grid development. Development finance institutions (DFIs) are increasingly focusing on creating enabling environments, supporting policy and regulatory reforms, and investing in important regional infrastructure to attract mainstream commercial investment [16].

A major innovation opportunity lies in moving beyond providing basic lighting and phone charging towards utilizing solar energy to power economic activities [56]. This concept of productive use of energy is widely seen as necessary for making electrification economically sustainable, creating local value, improving livelihoods, and driving broader development impacts [57]. Applications include solar-powered irrigation for agriculture, energy for small and medium enterprises (SMEs), powering commercial centers, supporting local manufacturing, and enabling digital services [58]. Realizing this potential requires deploying solar solutions—primarily robust mini-grids or reliable grid connections—that can provide higher tiers of energy service (sufficient capacity and reliability) compared to basic SHS [59].

These innovations, particularly in financing mechanisms and the application of digital technologies are important for overcoming the persistent barriers to solar penetration in SSA [60]. They demonstrate a growing understanding of the need to adapt global technological advancements to local contexts, thereby unlocking new pathways for efficient and resilient energy service delivery [61].

3.8 Overall status summary

Installed solar capacity in SSA remains low (~1% of global total [6]), despite vast potential. Figure 3 present installed solar PV capacity in selected SSA countries, indicating variations in adoptions and projecting South Africa as a majority leader in solar energy deployment in SSA.

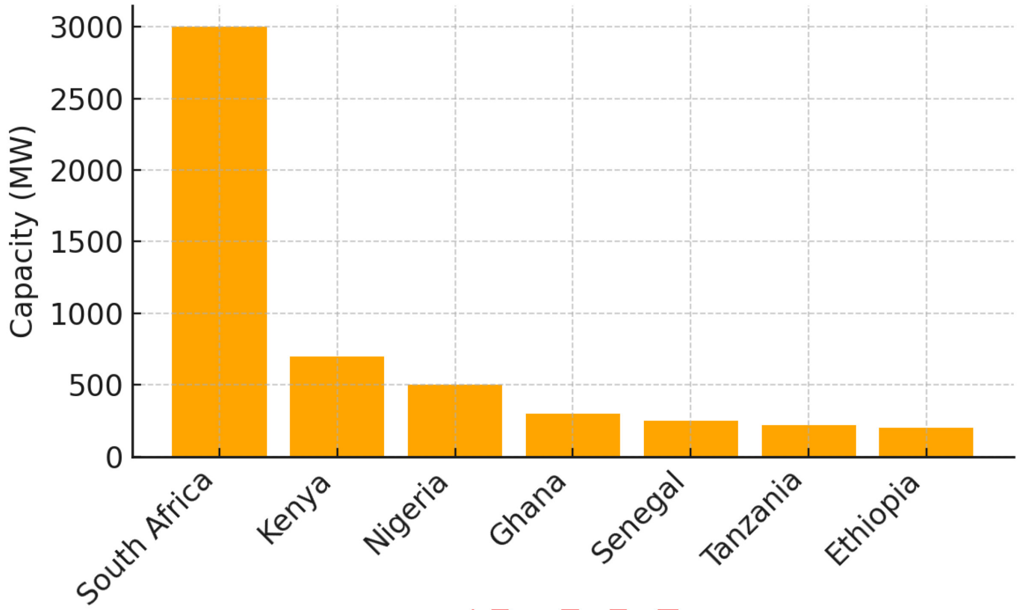

Figure 3: Installed Solar PV Capacity in Selected SSA Countries

According to data from the IEA, the total installed renewable energy capacity in SSA reached over 35 GW by the end of 2022., with a goal of 300 GW by 2030 [28]. Solar PV leads new capacity additions [6], but the overall energy mix is still dominated by traditional biomass and fossil fuels [16]. Investment grew tenfold from 2000-2009 averages to USD 5 billion/year in 2010-2020 [62] (see Table 5), but this is only ~2% of global renewable investment [62] and far below the estimated USD 20-50 billion needed annually for SDG7 [63]. Investment is also highly concentrated in a few countries [64]. A positive sign emerged in 2023 when SSA solar/wind investments surpassed fossil fuel investments for the first time [64]. Progress is uneven, with significant disparities in access rates between countries (See

Table 4for selected country specifics). A key concern is the potential decoupling of basic access connections from the delivery of reliable, sufficient power needed for economic development [63].

Table 4: Comparative electricity access indicators in selected SSA Countries (2022)

Country	Total Access Rate (%)	Urban Access Rate (%)	Rural Access Rate (%)	Total Without Access (Million)	Urban Without Access (Million)	Rural Without Access (Million)
Cameroon	65.1	96.7	24.8	9.46	0.46	9
Chad	11.3	32	1	17.25	2.91	14.34
DRC	21	41	1	83.09	23.88	64.64
Ethiopia	54.2	95.7	42.3	56.94	2.03	46.37
Ghana	88.8	95.6	77.5	3.68	0.73	2.95
Kenya	76.5	100	65	12.74	0	12.74
Malawi	14.5	53.6	7.3	18.06	1.62	16.44
Mozambique	39.5	80.6	27.2	18.91	1.39	17.52
Niger	19	64.9	6.8	21.05	1.48	19.57
Nigeria	55.4	83.6	37.1	88.58	10.59	77.99
South Africa	90.7	99.4	73.8	5.16	0.36	4.8
Tanzania	40.5	77.3	28.5	38.65	3.19	35.46
Uganda	42.1	85.9	33.6	30.22	2.21	28.01
Zambia	31.3	79.5	15.6	12.8	1.1	11.7
Zimbabwe	52.7	92.5	38.9	7.55	0.55	7

****Sources:*** *IEA - "SDG7: The Energy Progress Report 2024", World Bank - "Tracking SDG 7: The Energy Progress Report", IRENA - "Renewable Capacity Statistics 2024".*

Table 4 vividly illustrates the stark disparities in electricity access across the studied countries. South Africa and Ghana, with high electrification rates (89.8% and 88.8%), benefit from substantial installed capacities and diverse energy mixes, though thermal dominance raises sustainability concerns. In contrast, Chad and Malawi face challenges, with electrification rates below 15% and minimal installed capacities (48 MW and 445 MW, respectively). The urban-rural divide is pronounced, with rural electrification rates as low as 1% in Chad and DRC, reflecting infrastructure gaps in remote areas.

The reliance on hydro in countries like DRC, Ethiopia, and Zambia highlights the potential for renewable energy but also vulnerabilities to climate variability. Kenya's diversified energy mix, including significant geothermal and wind contributions, offers a model for balancing renewable and non-renewable sources. However, the high thermal reliance in Nigeria and South Africa suggests a need for transitioning to cleaner energy to meet global sustainability goals. The large populations without electricity access, particularly in Nigeria and DRC, underscore the urgency of scaling up energy infrastructure. Rural areas, where the majority of unserved populations reside, require targeted interventions such as off-grid solar or microgrid solutions. The incomplete data for Senegal highlight the need for improved data collection to inform policy.

Table 5 further highlights the significant investment gap in renewable energy in SSA. While there has been growth in annual investment, it remains a minuscule fraction of global renewable energy investment and is critically insufficient to meet the region's energy needs and climate goals.

Table 5: Renewable Energy Investment Trends in SSA

Time Period	**Average Annual Investment (USD Billions)**	**Africa's Share of Global RE Investment (%)**	**Key Observations**	**Source**
2000-2009	< 0.5	Low	Early stage	[65]
2010-2020	5.0	~2 (IRENA) / ~1.7 (Climate Policy Initiative for SSA)	Significant growth, but still low globally	[65]
2021	~8 (Estimate)	< 1 (Recent years)	Investment levels remain far below needs ($20-50B/yr)	[66]
2023	-	-	SSA Solar/Wind investment surpassed fossil fuel investment for first time	[66]
2030	>200 (Total energy)	-	Massive scale-up required	[43]

Note: Figures represent estimates for Africa or SSA, depending on the source. Investment needs vary based on scenarios (e.g., SDG7 access vs. broader energy goals).

This underinvestment, coupled with the persistent energy access deficit despite immense solar potential, points to a profound systemic failure in translating abundant natural endowment into tangible energy access and development. The low installed capacity, despite high potential, suggests that external and internal barriers are effectively neutralizing a key comparative advantage. The review's core analytical challenge is to dissect why this paradox persists, emphasizing that the problem is not a lack of sun, but a lack of effective mechanisms to harness it, thereby justifying a comprehensive analysis of drivers and barriers.

4. FACTORS INFLUENCING SOLAR ADOPTION: DRIVERS AND BARRIERS

The adoption of solar energy in SSA is shaped by a dynamic interplay of enabling drivers and significant obstacles.

4.1 Key drivers

The most fundamental driver is the urgent need to address the region's profound energy poverty. With hundreds of millions lacking electricity, governments and development partners are actively seeking scalable and cost-effective solutions to achieve universal access, as mandated by SDG7 [16]. Initiatives like the World Bank's "Mission 300," aiming to connect 300 million people in Africa by 2030, heavily rely on renewable energy, particularly solar, to achieve these ambitious targets [46]. The sheer scale of unmet demand creates a powerful impetus for exploring and deploying solar solutions.

Solar energy's improving economics are among major catalyst for its adoption; the dramatic global decrease in the cost of solar PV modules (down 82% between 2010-2019 [16]) and, increasingly, battery storage systems [67], has fundamentally altered the energy landscape.

Solar PV is now the cheapest source of new electricity generation in many parts of Africa and is projected to outcompete all alternatives continent-wide by 2030 [68].Traditional energy sources in SSA often come with significant drawbacks [69]. Grid electricity, where available, is frequently unreliable and expensive, with consumers paying almost double the global average rate [67] and facing some of the world's highest connection charges [63]. Dependence on imported fossil fuels for generation exposes economies to volatile global prices. Diesel generators, commonly used for backup or off-grid power, are expensive to run, polluting, and reliant on often difficult fuel supply chains [70]. Solar offers a pathway to lower energy costs and greater price stability, particularly for off-grid populations and businesses seeking alternatives to diesel[71].

Numerous SSA countries have established national renewable energy targets and integrated solar energy into their electrification strategies and resource plans [72]. Examples include South Africa's Integrated Resource Plan (IRP) [38], Kenya's Off-Grid Solar Access Project (KOSAP) focusing on off-grid areas [36], NEP promoting mini-grids [36], and the national energy compacts developed under Mission 300 [46]. These plans provide signals to investors and guide development efforts. Twenty-eight SSA countries signed the 28th Conference of the Parties to the UN Framework Convention on Climate Change (COP28) pledge to triple renewable capacity [64]. Mechanisms like feed-in tariffs, net metering schemes (e.g., Botswana's Rooftop Solar Program [73]), subsidies (though often needing better targeting [6]), tax credits [27], and competitive auction programs (which have successfully driven down prices for utility-scale projects in countries like South Africa [67]) can significantly accelerate deployment when designed and implemented effectively.

Innovative Business Model like Pay-as-you-go (PayGo) financing, leveraging mobile money platforms, has been transformative for the SHS market [28]. By breaking down the upfront cost barrier, PayGo has enabled millions of low-income households to access basic solar energy services [74]. While PayGo primarily targets the SHS segment, its success demonstrates the power of adapting financial models to local contexts [75]. However, it is important to recognize that while PayGo effectively addresses consumer affordability for small systems, it does not inherently solve the much larger capital investment challenge required for scaling up infrastructure like mini-grids or utility-scale plants. These larger projects necessitate different financing structures, such as project finance, blended finance, and substantial public or development finance institution support [9]. PayGo is thus key innovation for distribution and access at the household level, but not a complete solution for financing the entire solar transition [76].

International Support & Investment from DFIs like the World Bank [35] and the AfDB [62], along with bilateral donors and climate funds, are significant sources of funding and technical assistance for solar projects in SSA [7]. Foreign direct investment (FDI) is also playing a role, particularly in larger projects, although overall investment levels remain far below what is needed [64]. Regional initiatives like the West African Power Pool (WAPP) [77] and large-scale programs like Mission 300 [46] aim to coordinate efforts and mobilize greater capital flows. Growing global and national focus on climate change provides a strong rationale for prioritizing solar energy solutions. Alignment with the Paris Agreement and subsequent climate pledges, such as the COP28 commitment to triple renewable energy capacity [64], encourages governments to adopt low-carbon energy strategies[78]. Solar energy is central to meeting these NDCs [79]. Reducing Local Pollution means shifting away from fossil fuels [28] and traditional biomass (like wood and charcoal, which dominate household energy use [80]). Solar technologies offers significant benefits, including improved air quality (both ambient and indoor) and reduced pressure on forest resources[81].

Improved technology and advances in PV efficiency and the increasing maturity and reliability of solar technologies, including storage solutions, enhance their attractiveness [1]. Energy Security and Independence for households and businesses grappling with unreliable grid supply or volatile fuel prices, solar systems (especially with storage) offer a path towards greater energy security and independence [7]. This is a particularly strong motivator for C&I customers and higher-income households [7]. The presence of supportive policies and targets is clearly a driving force for solar adoption [82]. However, the effectiveness of these policies is often contingent on the broader enabling environment [83]. Policy initiatives act primarily as catalysts, accelerating progress where underlying conditions like access to finance, institutional capacity, and functional market structures are reasonably adequate [63]. In contexts where these fundamentals are weak, even well-intentioned policies may fail to deliver results, explaining the persistent gap between ambitious targets and actual deployment observed in many SSA countries [1]. A holistic approach addressing finance, capacity, and market realities alongside policy design is therefore essential.

4.2 Major barriers

Finance consistently emerges as the primary bottleneck hindering solar deployment in SSA [9]. Although global solar PV prices have fallen dramatically, the initial capital investment required for solar systems – particularly larger installations like mini-grids or C&I rooftop systems – remains prohibitively high for many potential adopters, including households, businesses, and project developers [63]. Compounding this, imported machinery and equipment, including digital technologies, are often significantly more expensive in SSA (e.g., 35–39% higher than in the US) due to logistics, tariffs, and market inefficiencies [84]. High Cost of Capital (CoC) perhaps is the most critical financial barrier, high CoC (estimated at 11% or more for solar PV in SSA, compared to lower single digits in Europe) drastically increases the overall cost of solar projects, making many economically unviable and deterring investment [64]. Analysis suggests that lowering the CoC closer to European levels could unlock nearly 100 GW of additional solar PV capacity by 2050 [64]. Investments in SSA, even using mature technologies like solar PV, are perceived as carrying higher risks compared to other regions [85]. These risks stem from factors including policy and regulatory uncertainty, currency fluctuations, political instability, and perceived counterparty risk (e.g., reliability of utility off-takers) [86]. This results in a 'risk premium' being applied, leading to significantly higher interest rates and equity return expectations [64]. Limited Access to Finance for both project developers seeking large-scale funding and end-users (households and small businesses) needing credit to purchase systems face significant difficulties in accessing appropriate and affordable finance [67]. Local financial institutions may lack the expertise or risk appetite for renewable energy lending. Public funding is insufficient to meet the vast investment needs, and mechanisms to effectively mobilize private capital are often underdeveloped [9]. The annual financing gap to meet SDG7 access goals is estimated to be enormous, ranging from USD 20 billion to USD 50 billion [80].

Weak or unstable governance structures create significant hurdles; many SSA countries lack clear, comprehensive, stable, and supportive policy and regulatory frameworks specifically designed for solar energy, particularly for decentralized solutions like mini-grids [33]. Frequent policy changes, political interference, and lack of long-term strategic vision create uncertainty for investors [38]. Complex, lengthy, and non-transparent permitting processes, often involving multiple agencies beyond the energy sector (e.g., environmental clearances, land rights, business licenses), can cause significant delays and increase project costs [33]. National electricity utilities in many SSA countries suffer from poor operational and financial performance, hindering their ability to act as reliable off-takers for grid-tied projects or effectively manage grid integration [9]. Regulatory bodies may lack the resources, independence, or technical expertise to oversee the sector effectively, particularly the rapidly evolving mini-grid market [33]. Overall weak state capacity limits the ability to plan, implement, monitor, and enforce energy policies and regulations [9].

Setting appropriate tariffs is also a challenge; grid tariffs are often not cost-reflective due to subsidies or political pressures, making it difficult for utilities to invest or for independent power producers (IPPs) to compete [80]. For mini-grids, finding a balance between cost recovery for the operator and affordability for low-income consumers is complex [33]. High grid connection charges also act as a significant barrier to access for poorer households [67]. Market structures and logistics present significant obstacles, solar markets in many SSA countries are relatively nascent, lacking maturity, robust competition, and well-established local supply chains for equipment and spare parts [63]. This can lead to higher costs and limited availability of products and services. The influx of low-quality, substandard, or counterfeit solar products (particularly SHS components, batteries, and solar water pumps) is a major problem in several markets [87]. These products often fail prematurely, leading to financial losses for consumers and damaging trust in solar technology [87]. This issue is exacerbated by weak regulatory oversight and a lack of enforced quality standards and product certification mechanisms [87].

Social dynamics and environmental factors also play a role, top-down project implementation without adequate community consultation and involvement can lead to conflicts over land use, lack of local buy-in, vandalism, and ultimately, project failure [7]. Establishing clear and sustainable ownership and management models for community-based systems like mini-grids is vital but often challenging [88]. Also potential adopters, particularly in rural areas, often lack sufficient and reliable information about the different solar technology options, their costs and benefits, financing possibilities, and reputable suppliers or installers [7]. Site-specific environmental conditions can pose challenges. Dust accumulation on panels can significantly reduce energy output, requiring regular cleaning [87]. Equipment may be vulnerable to damage from lightning strikes or flooding in certain areas [63]. For applications like solar irrigation, water scarcity or poor groundwater quality (e.g., salinity, high iron content) can limit viability [63].

These barriers are not independent but are deeply interconnected. For instance, policy instability [33] directly contributes to the high perceived risk that inflates the cost of capital [64], thereby worsening the financial constraints. Weak institutional capacity [9] undermines effective policy implementation and market regulation, which in turn allows poor-quality products to proliferate [87] and deters credible investors. Grid limitations [80] necessitate off-grid solutions, but these solutions then face their own set of financing, regulatory, and market barriers. This interconnectedness means that tackling barriers in isolation is unlikely to succeed; holistic, systems-level interventions are required. Furthermore, many of these challenges are significantly amplified in the remote rural areas where the majority of the unelectrified population resides [6]. The "last mile" delivery of solar products and services faces compounded difficulties related to poor infrastructure [84], higher logistical costs, scarcity of technical skills [87], difficulties in providing maintenance and repairs [87], and limited access to information and finance [7]. Overcoming these amplified barriers requires specifically tailored strategies, potentially involving higher levels of subsidy, dedicated rural capacity-building programs, and robust support for developing resilient rural supply chains. The SWOT analysis (Table 6) provides a comprehensive overview of strengths, weaknesses, opportunities, and threats affecting solar technology penetration in SSA. To move beyond descriptive categorization, we applied a pairwise comparison matrix (Table 7) and AHP ranking (Table 8).

Table 6: SWOT analysis

Strengths:	i. Abundant solar resources (60% of global best) ii. Falling PV and battery costs (82–89% decrease since 2010)

	iii. Growing SHS market, PayGo models iv. Regional experience with mini-grids (e.g., Tanzania, Nigeria) v. Rising political will (COP28 pledges)
Weaknesses:	i. Low installed capacity (~1% of global solar PV) ii. High energy access deficit (>600M without electricity) iii. Weak and unstable grid infrastructure iv. Prohibitively high upfront costs, high cost of capital (>11%) v. Policy instability and institutional fragmentation vi. Limited local technical capacity vii.
Opportunities:	i. Immense unmet energy demand (population growth, urbanization) ii. Continued technology innovation (AIoT-enabled solar, hybrid systems) iii. Productive use applications (irrigation, SMEs, digital services) iv. Climate financing and international donor support v. Regional power pools and cross-border integration vi. Job creation and local manufacturing opportunities
Threats:	i. Persistent poverty, low affordability ii. Political instability in fragile states iii. Currency fluctuations and forex risks iv. Influx of counterfeit and substandard solar products

	v. Climate impacts on infrastructure (dust, floods, heatwaves) vi. Financing gap (USD 20–50B/year needed) vii.

Table 7: Pairwise comparison of SWOT groups (Saaty Scale)

SWOT Category	Strengths	Weaknesses	Opportunities	Threats	Priority Weight
Strengths	1	1/3	1/2	2	0.19
Weaknesses	3	1	2	4	0.42
Opportunities	2	1/2	1	3	0.26
Threats	1/2	1/4	1/3	1	0.13

Consistency Ratio (CR) = 0.08 < 0.1 (acceptable)

Table 8: Ranked factors by weighted importance

Rank	Factor	Weight
1	High cost of capital & financing barriers	0.21
2	Weak/unstable grid infrastructure	0.18
3	Policy instability & weak institutions	0.14
4	Abundant solar resources	0.11
5	Falling technology costs	0.09
6	Immense unmet demand	0.08
7	Counterfeit/low-quality products	0.07
8	Political instability & currency risks	0.06
9	Productive use opportunities (agriculture, SMEs)	0.04
10	Climate risks (dust, flooding, variability)	0.02

The SWOT–AHP analysis revealed that financial barriers (high cost of capital) and infrastructure weaknesses carry the greatest weight in influencing solar penetration outcomes. These findings provide structured prioritization absent in prior literature. The solutions proposed are establishment of blended finance mechanisms and concessional lending facilities to reduce high cost of capital, investment in transmission/distribution upgrades and decentralized mini-grids, adoption of stable, long-term renewable energy policies and enforcement of transparent regulatory frameworks, development of regional solar product certification and enforcement systems to curb counterfeit imports, and mobilization of regional energy security funds as well as promotion of local manufacturing to reduce import dependency. Financial de-risking, infrastructure investment, and regulatory stability—directly address the most important obstacles while using key strengths (abundant resources, falling costs) to the regional advantage. This structured evaluation enhances the strategic value of this review, moving beyond descriptive synthesis to decision-oriented guidance.

5. CASE STUDIES, COMPARATIVE INSIGHTS AND FUTURE OUTLOOK

Despite the numerous challenges, SSA features several examples of progress and innovation in solar energy deployment [89]. These case studies, while context-specific, offer valuable lessons and demonstrate the potential for solar technologies to contribute to electrification and development goals.

5.1 Success stories and diverse approaches

Kenya is widely recognized as a leader in the off-grid solar sector, particularly for SHS adoption [90]. This success has been significantly fueled by the widespread penetration of mobile money platforms (notably M-Pesa), which enabled the rapid scaling of PayGo business models [74]. Companies like Azuri Technologies have established significant operations here [74]. Beyond SHS, Kenya is actively pursuing mini-grid development through initiatives like KOSAP, which aims to establish nearly 150 mini-grids in underserved counties [36]. With a relatively high electrification rate for the region and strong policy support, Kenya is considered on track to achieve universal access by 2030 [6].

Despite facing significant challenges with grid reliability and access, Nigeria has placed a strong emphasis on decentralized solutions, especially mini-grids [27]. The government's NEP, supported by the World Bank, has adopted a market-driven approach, providing grants and fostering private sector participation, which has catalyzed the development of over 100 solar mini-grids [36]. Nigeria is considered one of the most promising markets for mini-grid development on the continent [7]. Additionally, the World Bank's distributed access through renewable energy scale-up (DARES) project aims to benefit over 17.5 million Nigerians through SHS and mini-grids, explicitly targeting the replacement of polluting diesel generators [46]. Identified alongside Nigeria as a promising market for mini-grids [7], Senegal often views mini-grids as the preferred solution after grid extension [27]. The country benefits from concessional finance and equity playing a significant role in renewable energy projects [64] and participates actively in regional initiatives like the WAPP [91].

Tanzania has relatively long-standing experience with mini-grids, initially including hydro and biomass systems, but increasingly focusing on solar [33]. The country has developed specific regulatory frameworks for mini-grids under the Energy and Water Utilities Regulatory Authority (EWURA), evolving from fixed feed-in tariffs to more flexible systems, including competitive bidding for solar projects [33]. This demonstrates an adaptive regulatory approach based on experience. Several World Bank projects support mini-grid scale-up and solar development [33], and PayGo operators are active [74]. Rwanda stands out for its strong government commitment and integrated planning approach towards achieving universal energy access, which it is on track to meet by 2030 [48]. The country employs a mix of grid extension, mini-grid deployment, and SHS distribution, demonstrating the importance of political will and coordinated strategy [77]. Infrastructure development from science and technology institutions has also been noted as instrumental [77].

Possessing the most developed power sector in SSA, South Africa has implemented large-scale renewable energy procurement primarily through its Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), which utilized competitive auctions to drive down costs for utility-scale solar PV and wind projects [92]. The country also has a rapidly growing rooftop solar market, particularly in the C&I segment, driven largely by chronic power shortages (load-shedding) from the national utility, Eskom [93]. However, South Africa faces immense challenges related to grid capacity constraints, coal dependency transition issues, and social equity concerns [94].

Ghana; with one of the highest electrification rates in SSA [4], Ghana is also on track for full access by 2030 [48]. It plays an active role in regional power trade through WAPP [91], facilitating the exchange of electricity, potentially including solar power, with neighboring countries. Despite having one of the largest access deficits [3], Ethiopia is making progress, leveraging its significant hydropower resources while also exploring solar potential. The government is developing mini-grid regulations [36] and participates in regional interconnection projects aimed at facilitating power trade [46].

These case studies collectively reveal that there is no single blueprint for success in deploying solar energy in SSA. Different countries leverage distinct strengths and adopt varied strategies. Kenya's success in SHS is tied to its unique mobile money ecosystem, while Nigeria's progress in mini-grids relies on a specific market-based regulatory framework. South Africa's utility-scale deployment was driven by auctions, whereas Rwanda emphasizes strong state-led planning. This diversity underscores the importance of tailoring approaches to the specific national context, considering factors like regulatory capacity, market maturity, existing infrastructure, financial landscape, and political economy. Attempting to simply replicate a model from one country to another without careful adaptation is unlikely to yield optimal results.

Furthermore, the prominent role of international development finance, particularly from institutions like the World Bank [35], highlights a shift in approach. While direct project funding remains important, there is an increasing emphasis on creating enabling environments. This involves supporting policy and regulatory reforms [33], designing market-based mechanisms to attract private investment (like in Nigeria's NEP [36]), investing in critical regional infrastructure (like transmission lines [91]), and using public or concessional funds strategically to de-risk projects and "crowd in" private capital [36]. This evolution suggests a growing motivating factor suggests a growing understanding that achieving sustainable, large-scale solar deployment requires building robust local markets and institutions, moving beyond reliance on grant-funded pilot projects towards models that can attract mainstream commercial investment.

5.2 Policy frameworks and governance

Effective policy frameworks and robust governance are paramount for accelerating solar technology penetration in SSA. While many countries have established ambitious targets, the implementation and effectiveness of these policies vary significantly. This section synthesizes insights from successful approaches, regulatory evolution, and lessons learned across different countries.

The presence of supportive policies and targets acts as a significant driving force for solar adoption. Many SSA countries have integrated solar energy into their national renewable energy targets and broader electrification strategies [95]. Examples include South Africa's IRP, Kenya's KOSAP focusing on off-grid areas, and NEP promoting mini-grids. These plans provide clear signals to investors and guide development efforts, as evidenced by the COP28 pledge signed by twenty-eight SSA countries to triple renewable capacity [13]. Mechanisms such as feed-in tariffs, net metering schemes (e.g., Botswana's Rooftop Solar Program), subsidies, tax credits, and competitive auction programs (which have successfully driven down prices for utility-scale projects in countries like South Africa) can significantly accelerate deployment when designed and implemented effectively [13].

However, the effectiveness of these policies is often contingent on the broader enabling environment. Policies primarily act as catalysts, accelerating progress where underlying conditions like access to finance, institutional capacity, and functional market structures are reasonably adequate [96]. In contexts where these fundamentals are weak, even well-intentioned policies may fail to deliver results, explaining the persistent gap between ambitious targets and actual deployment observed in many SSA countries. This highlights the necessity of a holistic approach that addresses finance, capacity, and market realities alongside policy design [13]. Conversely, weak or unstable governance structures create significant hurdles. Many SSA countries lack clear, comprehensive, stable, and supportive policy and regulatory frameworks specifically designed for solar energy, particularly for decentralized solutions like mini-grids [97]. Frequent policy changes, political interference, and a lack of long-term strategic vision create uncertainty for investors. Complex, lengthy, and non-transparent permitting processes, often involving multiple agencies beyond the energy sector (e.g., environmental clearances, land rights, business licenses), can cause significant delays and increase project costs [97].

National electricity utilities in many SSA countries often suffer from poor operational and financial performance, hindering their ability to act as reliable off-takers for grid-tied projects or effectively manage grid integration [98]. Regulatory bodies may lack the resources, independence, or technical expertise to oversee the sector effectively, especially the rapidly evolving mini-grid market. Overall weak state capacity limits the ability to plan, implement, monitor, and enforce energy policies and regulations [98]. Setting appropriate tariffs is also a challenge; grid tariffs are often not cost-reflective due to subsidies or political pressures, making it difficult for utilities to invest or for IPPs to compete[99]. For mini-grids, finding a balance between cost recovery for the operator and affordability for low-income consumers is complex. High grid connection charges also act as a significant barrier to access for poorer households [99].

5.3 Comparative analysis and key variations

Electrification rates across various nations show stark contrasts. Island nations such as Seychelles and Mauritius have achieved universal (100%) electricity access, while countries like Gabon (93.5%), South Africa (86.5%), and Ghana (85.1%) also demonstrate relatively high electrification levels. However, a significant number of other countries, including South Sudan (8.4%), Burundi (10.3%), Chad (11.7%), Malawi (14.0%), Central African Republic (15.7%), and both Burkina Faso and Niger (19.5%), have access rates below 20% [4]. This wide variation underscores the uneven nature of development and electrification efforts across the continent.

Countries are employing different policy approaches to address electrification. South Africa has pioneered large-scale renewable energy auctions (REIPPPP) [92]. Nigeria and Tanzania have concentrated on developing specific regulatory frameworks to encourage private sector participation in the mini-grid market [33]. Rwanda exemplifies a strong, state-led, integrated planning approach that combines grid extension with off-grid solutions [77]. Kenya has successfully cultivated a dynamic market for SHS by implementing enabling policies that support PayGo models [36]. Geographically, activity in off-grid solar and mini-grid initiatives appears prominently in East Africa (Kenya, Tanzania, Ethiopia, Rwanda) and West Africa (Nigeria, Senegal, Ghana) [7]. West Africa, despite having a higher average electricity access rate (53%) compared to SSA overall, still exhibits significant internal variation and a large rural-urban divide [100]. Investment flows also show a tendency to concentrate in a limited number of countries perceived as having more favorable conditions [64].

Financing approaches also differ across countries and project types; the capital structure of renewable energy projects varies. In South Africa's utility-scale market, projects have been predominantly financed through debt. In contrast, Senegal has seen a greater role for concessional finance (lower-interest debt) and equity investment [64]. Mini-grid financing involves a spectrum of models. Some are primarily grant-funded, often as pilot or demonstration projects [33]. Others rely on purely private investment, driven by market-based regulations (as encouraged in Nigeria [36]). Increasingly, public-private partnerships (PPPs) and blended finance approaches are being explored, using public or donor funds to de-risk projects and attract private capital [36].

5.4 Opportunities and future outlook

The most significant opportunity lies in the sheer scale of unmet energy needs. With over half a billion people still lacking electricity [48] and hundreds of millions more suffering from unreliable supply, the potential market for solar solutions is enormous. This demand is set to grow substantially due to rapid population growth (SSA's population projected to double by

2050 [9]) and accelerating urbanization and economic development aspirations [48]. Meeting this rising demand sustainably presents a massive opportunity for solar deployment across all scales.

The global trend of falling costs for solar PV and battery storage is expected to continue, further enhancing the economic competitiveness of solar solutions in SSA [1]. Ongoing improvements in panel efficiency, battery energy density, and system integration will make solar increasingly viable for a wider range of applications. Furthermore, advancements in enabling technologies like smart grids, digitalization for remote monitoring and payment systems [1], and innovative hybrid system configurations (such as floating solar PV combined with hydropower [101]) offer new pathways for efficient and resilient energy service delivery.

While current investment levels are inadequate, there is significant potential to mobilize the capital required for SSA's solar transition. Achieving universal access by 2030 necessitates annual investments ranging from USD 20 billion to USD 50 billion [80]. Closing this gap requires a multi-pronged approach: increased commitments from governments and DFIs, substantial mobilization of private sector capital, and innovative financing mechanisms [48]. Creating more stable and attractive policy and regulatory environments is key to reducing perceived risks and lowering the cost of capital [64]. Strategically using public and concessional finance to de-risk investments and "crowd in" private finance will be crucial [36]. Additionally, revenues generated from the extraction and processing of key minerals found in the region could, if managed transparently and effectively, provide a domestic funding source for renewable energy investments [9].

A major opportunity lies in moving beyond providing basic lighting and phone charging towards utilizing solar energy to power economic activities [48]. Applications such as solar-powered irrigation for agriculture [48], energy for SMEs, powering commercial centers, supporting local manufacturing, and enabling digital services. This "productive use" of energy is widely seen as important for making electrification economically sustainable, creating local value, improving livelihoods, and driving broader development impacts [67]. However, realizing this potential requires deploying solar solutions – primarily robust mini-grids or reliable grid connections – that can provide higher tiers of energy service (sufficient capacity and reliability) compared to basic SHS [33].

Strengthening regional cooperation and expanding cross-border electricity transmission infrastructure offers significant opportunities [91]. Integrated regional power pools (like WAPP, East African Power Pool (EAPP) and South African Power Pool(SAPP)) allow countries to share diverse energy resources (hydro, solar, geothermal) across larger geographical areas, smoothing out variability, benefit from economies of scale by developing larger, more efficient generation plants (including utility-scale solar farms) that might be too large for individual national markets, improve overall grid stability and reliability through interconnected networks and reduce overall system costs and investment needs [91]. Continued investment in transmission interconnections is key to unlocking these benefits [46]. There is considerable scope for improving and harmonizing policy and regulatory frameworks across the region [1]. Adopting best practices identified through comparative analysis, streamlining bureaucratic processes (especially permitting [33]), ensuring policy stability, and strengthening institutional capacity can create more predictable and attractive environments for solar investment [64]. A shift towards comprehensive, long-term energy planning centered on productive use and sustainability is needed [67].

The transition to solar energy can be a significant engine for job creation across SSA [1]. Employment opportunities arise in manufacturing and assembly (where feasible), project development, installation, operations and maintenance, sales and distribution, and supporting services. IRENA estimates substantial job creation potential from investments in renewables and energy efficiency in Africa [62]. Furthermore, there is an opportunity to develop local supply chains and potentially add value to the key minerals extracted in the region, rather than just exporting raw materials. The presence of vast reserves of critical minerals (like cobalt, lithium, copper, manganese) essential for batteries, wind turbines, and other clean energy technologies presents both a major opportunity and a potential pitfall for SSA [9]. The opportunity lies in leveraging these resources to generate substantial revenues, potentially funding domestic development priorities including renewable energy deployment, and fostering local processing and manufacturing industries to capture more value domestically [9]. However, Africa's history is replete with examples of the "resource curse," where abundant mineral wealth failed to translate into broad-based sustainable development due to poor governance, corruption, lack of transparency, and failure to invest revenues wisely; there is a significant risk that critical minerals could follow this pattern. Avoiding this trap requires proactive and robust governance frameworks, transparent revenue management systems, and deliberate policy choices that explicitly link mineral extraction to national sustainable development goals, including investing significantly in building Africa's own clean energy infrastructure [9].

5.5 Addressing literature gaps and future research directions

Despite the growing body of literature on solar technology penetration in SSA, several gaps remain, highlighting fertile ground for future research. Addressing these gaps is key for informing more effective policy and investment strategies. One significant observation from this review is that most literature sources on solar technology rely on aggregated secondary data from international organizations, with less emphasis on primary research or peer-reviewed empirical studies originating directly from SSA. This suggests a "data desert" at the local level, where granular, context-specific insights are often lacking. While international reports provide valuable macro-level overviews, they may inherently overlook the nuanced socio-economic, cultural, and political factors that influence solar adoption at the community level. Future research should prioritize localized, empirical studies that involve direct data collection from diverse communities and projects across SSA. This includes detailed ethnographic studies on energy consumption patterns, willingness-to-pay analyses, and the social impacts of different solar interventions.

There is a need for more in-depth comparative analyses of policy effectiveness across different SSA countries. While this review highlights various policy approaches, a deeper understanding of why certain policies succeeds or fail in specific contexts, considering varying institutional capacities and political economies, is essential. Future research could employ robust econometric methods or qualitative comparative analysis (QCA) to identify the causal mechanisms linking policy design to actual solar deployment outcomes. This would help in formulating evidence-based policy recommendations that are truly adaptable to diverse national realities.

Furthermore, while the review touches upon innovative financing models like PayGo, there is a gap in comprehensive long-term impact assessments of these models, particularly regarding their scalability beyond basic SHS to mini-grids and productive uses. Research is needed on the long-term financial sustainability of these models, their impact on consumer debt, and their potential to attract larger-scale commercial investment. This includes exploring the role of local financial institutions and developing tailored financial products that address the high cost of capital and perceived risks for solar projects in SSA. Another area requiring further investigation is the interplay between solar deployment and broader development outcomes. While the potential for productive uses of solar energy is acknowledged, more empirical research is needed to quantify the specific economic and social impacts of solar-powered agriculture, small businesses, and community services. This could involve longitudinal studies tracking changes in income, employment, health, and education outcomes in communities with improved solar access.

Finally, research on quality control and standardization mechanisms for solar products in SSA is important. The prevalence of low-quality or counterfeit products undermines trust and hinders sustainable market development. Future studies could explore effective regulatory frameworks, certification processes, and consumer protection mechanisms to ensure the quality and reliability of solar technologies.

CONCLUSION

This comprehensive review distinguishes itself by synthesizing the latest data with an in-depth analysis of the interconnectedness of financial, policy, and infrastructural barriers, offering a holistic framework that identifies critical leverage points for unlocking scaled solar deployment across SSA. It uniquely highlights the paradoxical situation of SSA possessing 60% of global solar resources yet contributing only 1% of installed capacity, and emphasizes the recent, concerning trend of increasing energy access deficits in the region. This review is particularly timely given the recent confluence of factors; plummeting costs, escalating demand, growing political will, shifting investment patterns and global energy crises further exacerbating SSA's energy deficit. The landmark COP28 pledge by 28 SSA countries to triple renewable capacity, and the critical juncture where falling solar and battery costs intersect with innovative financing models like PayGo presents a window of opportunity for SSA to leapfrog traditional, carbon-intensive development paths. Understanding the current landscape in light of these shifts is important for effective policymaking and investment.

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