Review

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Posted Date: 14 March 2024

doi: 10.20944/preprints202403.0300.v2

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Review

A Review on the Present and Future of Solar Power in Africa

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Abstract: This paper provides a study on the development of solar energy, its prospects, and its impacts in Africa. Although the main focus is on technologies adopted for different uses (solar farms, mini-grids, off-grid, solar houses, irrigation, lighting, etc.), we also consider some aspects that increase the adoption of solar energy, such as legislation and business models. Finally, we will examine current and future solar projects managed by NGOs and international companies and how they benefit to leveraging social and economic standards, quality of life as well as capacity building in Africa. This study shows the plethoric interest of institutions outside Africa in the market of solar energy in the continent and that there is no African strategy to increase its independency toward a sustainable development particularly through energy transition.

Keywords: solar energy; development; Africa; solar farms; mini-grids; off-grid; solar houses; irrigation; legislation; business models; NGOs; international companies

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1. Introduction

In the dynamic energy landscape of Africa, solar energy is emerging as a promising solution to persistent challenges related to aging electrical infrastructure and increasing energy demand. Although Africa still produces less than 100 TWh of energy on average until 2018, in stark contrast to China's over 4000 TWh, technological advancements have led to an over 80% reduction in the cost of solar PV over the past two decades.

The roots of energy challenges in Africa date back several years, with countries like South Africa facing difficulties since 2008. Faced with this reality, governments have taken measures, collaborating with independent power producers and adjusting regulations to encourage private electricity generation.

The escalating costs of electricity, marked by a dramatic increase in tariffs since 2007, underscore the urgency of finding affordable energy alternatives. Furthermore, power interruptions are exacerbated by issues of theft and vandalism of electrical equipment, such as copper cables.

Amidst these challenges, solar energy stands out as a transformative solution. Despite the inherent variability of this resource and the crucial need for education on its installation, technological advancements have significantly reduced the deployment costs of solar panels over the past two decades.

In this regard, Africa benefits from a considerable natural asset: its exceptional sunlight. With some of the highest sunlight levels in the world, the continent holds immense solar potential that, if harnessed optimally, could not only meet current energy needs but also promote sustainable and economically viable development.

Here are some very interesting references that address the topic of solar energy in Africa, ranging from [1–40]. These diverse sources cover a wide range of perspectives, from technical aspects to the socio-economic implications of adopting solar energy on the continent. Among these references, you will find research papers, articles from specialized journals, and case studies, providing a solid foundation to deepen the understanding of the challenges and opportunities related to solar energy in Africa. These references constitute a valuable resource for any researcher or professional interested in this ever-evolving field.

The paper is organized as follows: section 2 gives a global trend of number of publications in the last 2 decades; section 3 presents the context of solar power in Africa. In section 4, adopted solar technologies are listed for different applications; key-players in solar power in Africa are depicted in section 5. The paper ends with a general discussion, recommendations and a conclusion

2. Analysis of Publications

2.1. Publication Trends: Tracking the Number of Publications over Time

The number of publications on solar energy in Africa has seen an increase over the years, encompassing various types of media such as articles, journals, websites, etc. Figure 1 illustrates the diversity of publications dealing with solar energy in Africa between 2000 and 2023. One can see a consistent rise in the number of publications from year to year. This demonstrates the growing significance of solar energy as a high topic of attention in the African context.

The results presented in this paragraph are extracted from Google Scholar, highlighting the global interest in solar energy in Africa. The sun, considered another Africa's natural treasure, emerges as a key resource to meet energy needs, especially in areas where electrification is still limited. This trend underscores the urgency and importance of developing solar energy-focused initiatives to promote sustainable development and access to electricity on the continent. Additionally, the diversity of contributors, whether from Africa, Europe, the United States, or elsewhere, reflects international collaboration aimed at exploring opportunities and challenges related to the growing use of solar energy on the African continent.

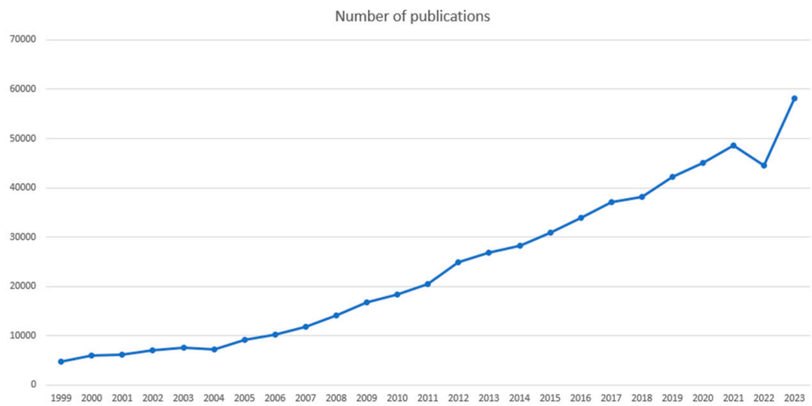

Figure 1. Dates of Publication.

2.2. Global Contribution to Solar Energy R&D in Africa

The figure (Figure 2) depicts a pie chart illustrating the number of publications on the subject of solar energy in Africa by various universities from France, England, South Africa, the United States, Germany, Canada, China, Morocco, Ghana, and Côte d'Ivoire. This visual representation allows for comparing the contribution of each country to research on solar energy in Africa.

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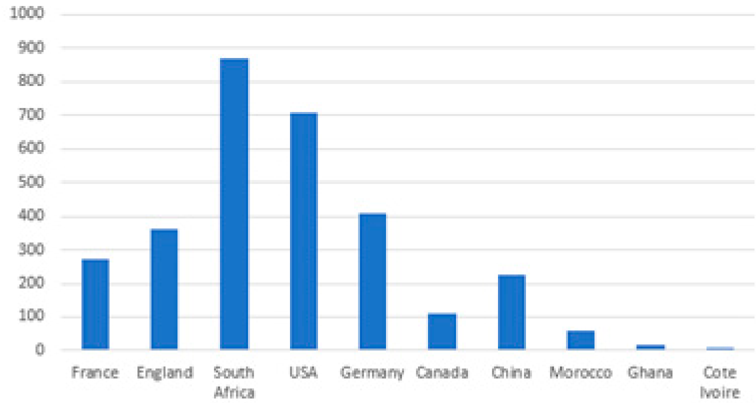

Figure 2. Global Contribution to Solar Energy Research in Africa.

2.3. Analysis of Solar Energy Publications in Africa (2013-2023): A Comparative Study across Various Application Domains

In this analysis, Figures 3–6 compare the number of publications on the topic of solar energy in Africa between the years 2013 and 2023, focusing on different application domains. Figure 3 depicts the curve of the number of publications for public lighting systems, Figure 4 for irrigation, Figure 5 for Solar Home Systems (SHS), and Figure 6 for mini-grids and off-grid systems. These curves provide a clear visualization of the evolution of the number of publications in each domain over this decade-long period. Analyzing this data will contribute to a better understanding of specific research trends in each solar energy application in Africa, offering valuable insights into the areas that garner the most attention and development over time.

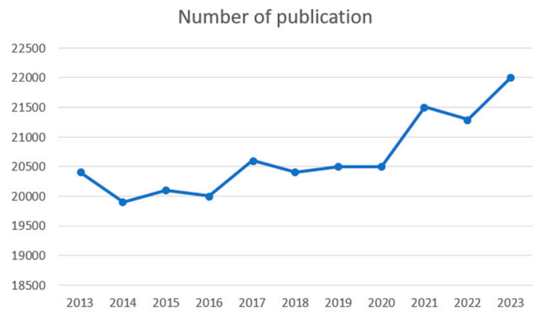

Figure 3. Public lighting system.

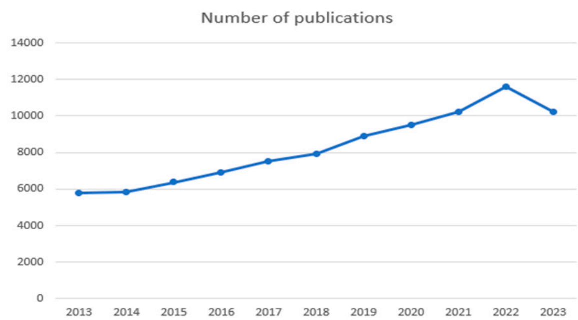

Figure 4. Irrigation.

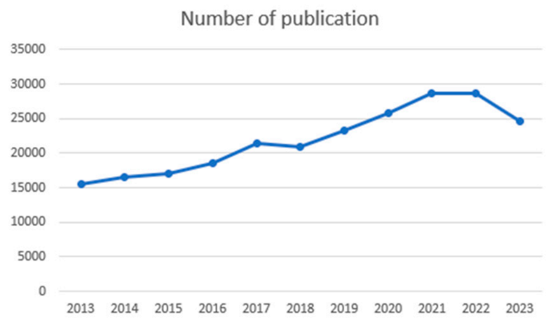

Figure 5. solar home system.

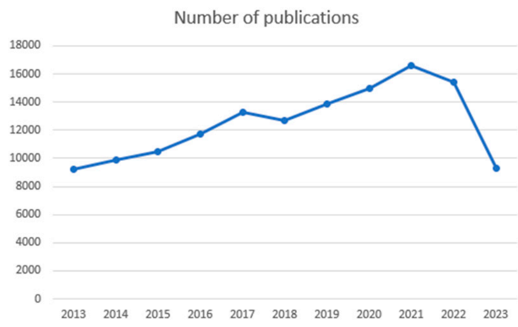

Figure 6. Mini-grid off grid.

3. Solar Energy: State of Play

3.1. Solar Potential

The solar potential, defined as the amount of available solar energy in a region, is closely tied to climatic and geographical conditions conducive to solar energy production. According to IRENA [1], the African continent receives an annual solar irradiation of 2,119 kilowatt-hours per square meter (kWh/m2), with most countries in North, West, and Southern Africa receiving over 2,100 kWh/m2 per year. The overall annual solar irradiation in Africa ranges from 1600 to over 2500 kWh/m²/year. Consequently, countries like Sudan, Egypt, and Chad can easily surpass 2400 kWh/m²/year of sunlight. On the other hand, regions such as Gabon and the southwest of Congo may experience approximately 1800 kWh/m²/year of sunlight. These findings underscore the diverse solar potential across the continent, presenting substantial opportunities for solar energy development in various parts of Africa [41]. Table 1 illustrates the Solar Potential of some African Countries.

Table 1. The Solar Potential in Some African Countries.

Country	Solar Potential
Egypt.	Egypt, ranked as the second sunniest country in the world after the United States, features particularly sunny regions such as Assuan and Abu Hamed, where one can expect to enjoy more than 10 hours of sunlight per day. The Egyptian climate is characterized by two distinct seasons: a mild winter from November to April and a hot summer from May to October [41].
South-Africa	The northern part of South Africa hosts the sunniest areas of the country, making it the second sunniest country in the world. The solar potential of South Africa is exceptionally high, exceeding 2,400 kWh/m² over most of the territory and even reaching over 2,500 kWh/m² in certain central and northern regions, comparable to the sunniest areas of the Sahara, Arabia, and northern Chile [42].

Algeria	Algeria has an estimated solar energy potential of 5.92 kWh/m2/day over a total area of 2.3 million km2, a significant figure. With an annual sunlight exposure of 3,000 hours, and specifically in Laghouat, it is estimated to be 1,800 hours per year [43].
Morocco	Morocco enjoys an exceptional solar potential, with annual irradiation values exceeding 2,200 kWh/m2 in the southern regions, especially in Western Sahara. The country experiences 3,000 hours of sunlight per year, with average irradiation surpassing 5 kWh/m², demonstrating considerable solar potential [44].
Senegal	Senegal holds one of the world's best solar potentials, with an average of 5.5 kWh/m²/day of raw solar energy. Its annual insolation level reaches 394 trillion kWh. Dakar receives nearly double the sunlight compared to Paris, with a stable distribution throughout the year [45].
Namibia	Namibia is ideally positioned for the production of photovoltaic and solar-concentration energy. With over 300 days of sunlight per year, clear skies, and a temperate climate, the solar production potential is immense. The achievable energy production by a large-scale photovoltaic system reaches 5.38 kWh/kWp/day, surpassing Germany by twice and China by 40%. Namibia competes only with Chile in photovoltaic energy production [46].
Tunisia	Tunisia, benefiting from a generously sunny climate, stands out due to its significant solar potential. With an average of over 3,000 hours of sunlight per year, southern regions, particularly around the Gulf of Gabes, experience peaks exceeding 3,400 hours. The northern part of the country records a minimal insolation period between 2,500 and 3,000 hours per year. Solar irradiation varies from 1,800 kWh/m²/year in the north to 2,600 kWh/m²/year in the south. The average global horizontal irradiation ranges from 4.2 kWh/m²/day in the northwest to 5.8 kWh/m²/day in the extreme south. These exceptional conditions make Tunisia an ideal site for harnessing solar energy.

By analyzing African countries, Table 2 categorizes them into five distinct groups based on their level of favourability to solar energy.

Table 2. Classification of African Countries Based on Solar Energy Favourability.

Countries extremely favoured	Countries very favoured	Favoured countries	Less favoured countries	Countries very little favoured
Egypt; Niger; South Africa	Ethiopia; Angola; Tanzania	Central African Republic; Mozambique; Tunisia	Ivory Coast; Cameroon; Democratic Republic of the Congo	Gabon; Republic of the Congo; Liberia

Figure 7 presented above provides a cartographic representation of solar potential in Africa, expressed in kilowatt-hours per kilowatt-peak (kWh/kWp) in each region of the continent. This map highlights the variation in solar potential across Africa, emphasizing areas with the highest levels of solar resources. The differentiated shades on the map illustrate the geographical distribution of solar potential, emphasizing the significance of certain regions as substantial sources of this energy resource [47].

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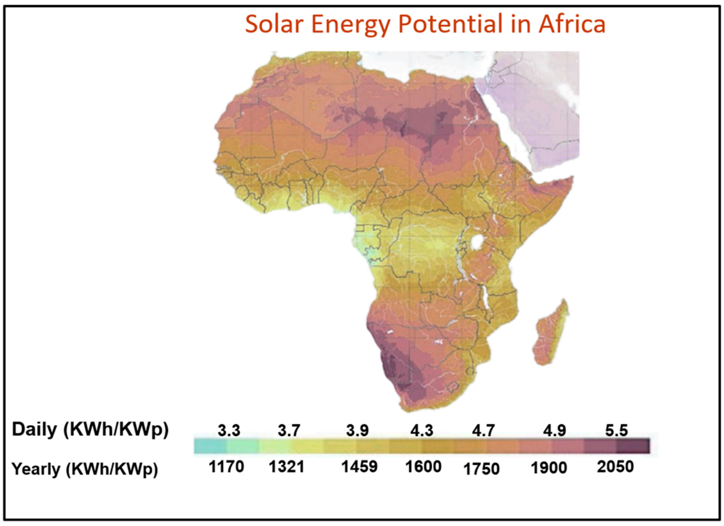

Figure 7. Photovoltaic power potential in Africa. Data from [48].

3.2. Legislation

The promotion and development of renewable energies in Africa are closely tied to the legislative frameworks in place across various countries on the continent. These legislations play a crucial role in establishing the necessary regulatory foundations to encourage investment and sustainable growth in the renewable energy sector. To illustrate the diversity of approaches adopted, Table 3 provides an overview of national legal frameworks, tariff policies, and specific incentives in effect in countries such as Morocco, Egypt, South Africa, and Algeria [49].

Table 3. Legal Frameworks, Tariff Policies, and Incentives in the Renewable Energy Sector.

Country	National legal framework	Tariff Policies	Incentive measures
Maroc	In Morocco, Law 82-21 supports individual solar energy production, enabling grid selling with tax incentives. Bill 40-19 reflects the country's commitment to stimulate investments and diversify renewable energy sources, strengthening investor confidence through an inclusive approach [7].	In Morocco, the commitment to renewable energies materialized through the establishment of a feed-in tariff of $0.34 per kilowatt-hour in 2011, aiming to stimulate major projects, notably the Noor Solar Power Complex in Ouarzazate. Law 13-09 on renewable energies complements this initiative by establishing competitive feed-in tariffs for electricity produced from renewable sources. Under the Moroccan Solar Plan, specific tariffs are defined for different segments of the solar sector, encouraging diversity in projects, whether large-scale or smaller in scope [10].	Tax Benefits: Exemption from VAT on importation and in the domestic market for water pumps using solar energy, as well as for all renewable energies in the agricultural sector. Subsidies and Financing Facilities: The Morseff program, which has mobilized 150 million euros since 2015, has successfully financed over 270 projects until the end of 2019, generating approximately 350,000 megawatt-hours per year. The European Bank for Reconstruction and Development (EBRD) has developed a Green Value Chain program aimed at

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			financing green technologies that integrate energy efficiency and rational resource use, with the support of the European Union, the Green Climate Fund, and South Korea. Tamwil el Fellah from Crédit Agricole has played a crucial role in financing around 3000 files with a financial envelope of approximately 200 million dirhams [14].
Egypt	In Egypt, the 2016 electricity legislation opened the sector to competition, establishing wholesale and retail markets. While the state-owned company EEHC retains control over production, transmission, and distribution, the private sector has had access since 1998. Tariff adjustments followed the reduction of energy subsidies between 2016 and 2020 as part of a program with the IMF. Egypt aims to achieve 42% of its electricity production from renewable sources by 2035, encouraging investments through competitive bidding for solar and wind projects, providing guaranteed tariffs for 20 to 25 years [9].	In Egypt, the Renewable Electricity Law (Law No. 203 of 2014) establishes incentive tariffs for electricity generated from renewable sources, thereby encouraging private investments. This legislation, combined with preferential pricing mechanisms and long-term purchase contracts, aims to ensure the profitability of solar projects. Concurrently, the Electricity Law grants tariff regulation powers to the regulatory body, provides more independence to the Egyptian Electricity Transmission Company (EETC), and fosters the establishment of a competitive market for end-users [11].	Tax Benefits: Equipment using solar energy enjoys VAT exemption on importation and in the domestic market. Subsidies and Financing Facilities: The program initiated by the European Bank for Reconstruction and Development (EBRD) in 2019 has mobilized significant funds to finance green technologies.
South Africa	In South Africa, the growth of solar energy is shaped by key legislation such as the Electricity Act of 2008 and the	In South Africa, the tariff policy for renewable energies aims at an economical and sustainable solution. Anticipated competitive costs (0.62 ZAR/kWh for solar and	Tax Benefits: Imported solar panels in South Africa are exempt from VAT, providing a 15% reduction in cost.

	National Policy on Renewable Energy of 2011, which establish a regulatory framework for the integration of renewable energies. These measures facilitate independent electricity supply, encourage private investments, and align with public-private partnerships to promote sustainable development in the solar sector.	wind by 2030) and the quick implementation turnaround (approximately 2 years) make renewable energies an attractive alternative [12].	Subsidies and Financing Facilities: The Renewable Energy Independent Power Producer Procurement Program (REIPPPP) provides financial incentives for independent solar energy producers in South Africa.
Algeria	In Algeria, the promotion of solar energy is supported by Law No. 02-01 of 2002 concerning electricity, encouraging the development of renewable energies with clear objectives. Law No. 04-09 of 2004 provides financial incentives, including favourable tariffs for the purchase of solar electricity, thereby fostering private investments [9].	In Algeria, Article 95 states that producers using renewable energies and/or cogeneration can benefit from premiums. These premiums are considered as diversification costs in accordance with Article 98. In other words, producers of renewable energy can receive financial incentives in the form of premiums to encourage the development of these energy sources [13].	Subsidies and Financing Facilities: The FNER contributes to the funding of electricity production projects from renewable energy sources and/or cogeneration systems. The FNER supports the establishment of certification and quality control organizations and laboratories for components, equipment, and processes related to electricity production from renewable energy sources. The fund finances projects aimed at harnessing renewable sources [15].

3.3. Existing Installations

Africa is experiencing significant progress in the field of solar energy, with over 1,100 existing installations, according to the International Energy Agency (IEA) [16]. Forecasts indicate a potential threefold increase in the continent's solar capacity by 2025 [49]. Currently, solar installations in Africa have a total capacity of 7.4 gigawatts spread across these 1,100 existing sites, Figure 8 illustrates the Top solar electricity-producing countries in Africa in 2020, solar electricity production reached 11,581 gigawatt-hours, marking a notable contribution of 1.4% for photovoltaics and 0.3% for solar thermodynamics to the continent's total production [50].

Figure 9 illustrates the impressive growth of solar electricity production in Africa from 2013 to 2020. The data shows a consistent increase in installed solar capacity over the years. In 2013, production was 361 gigawatt-hours (GWh), and it steadily rose each year, reaching a peak of 11,581 GWh in 2020. This progression highlights the rapid evolution of solar energy's contribution to the African continent, marking a significant advancement towards a sustainable energy transition [51].

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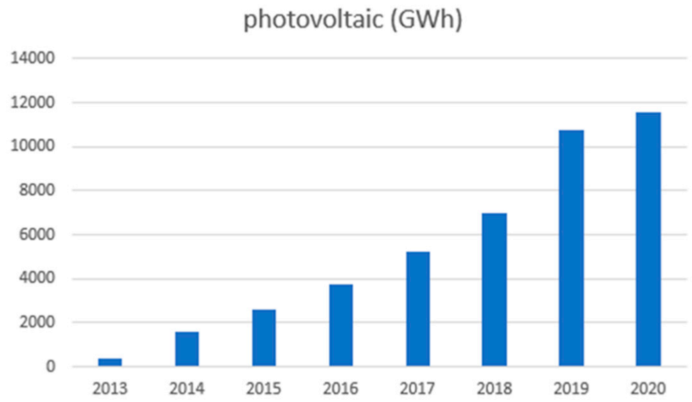

Figure 8. Solar electricity production in Africa (GWh). Data from [52].

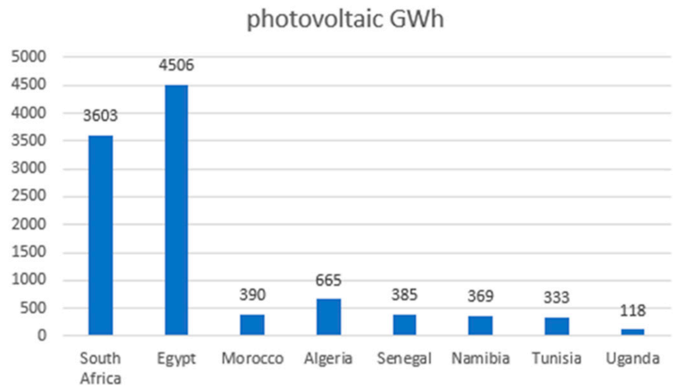

Figure 9. Top solar electricity-producing countries in Africa in 2020 GWh. Data from [53].

The geographical distribution of selected sites for solar electricity production is crucial for understanding the potential of solar energy across various African countries. These locations have been strategically chosen to assess and harness solar power, considering factors such as proximity to the equator, solar irradiance, and climatic conditions. The figure below (Figure 10) provides a visual representation of these selected sites, highlighting the diverse regions across Africa where solar energy production is being studied and developed.

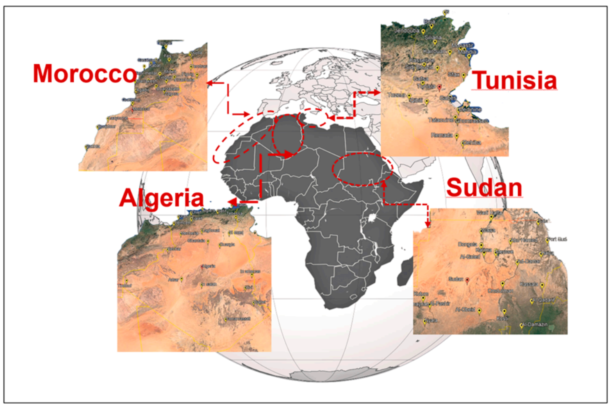

Figure 10. Geographical sites for solar electricity production in different African countries.

3.4. Funding and Business Models

In Africa, renewable energy projects are primarily funded through grants, which are favored for small-scale initiatives due to their compatibility with less developed financial sectors. Larger projects rely on subsidized borrowing, including concessional loans from regional development banks and green bonds from institutions like The World Bank and The African Development Bank. Public–Private Partnerships (PPPs) also play a role in leveraging public funds and reducing risks for private investors.

Financial de-risking, through external support, helps investors in solar energy projects by reducing risks and lowering investment costs. Institutions like the World Bank and African Development Bank provide substantial funding for renewable energy projects in Africa, offering various financial options and guarantee products to attract private investment. Multilateral donors like the Global Environment Facility Trust Fund (GEFTF) and the Global Energy Efficiency and Renewable Energy Fund (GEEREF) also play a role, supporting small and medium-sized projects in Africa through Public–Private Partnerships.

The European Investment Bank (EIB) significantly supports energy projects in Africa, with about 15% of its 2017 investments directed to Sub-Saharan Africa. Using diverse funding methods such as local currency, equity, and debt, the EIB fosters successful initiatives like Scaling Solar Zambia, which is set to expand to other African nations like Ethiopia and Madagascar. To supplement public finance, the EIB and other donors create investment mechanisms to attract private sector participation. Countries seeking international funds must define their requirements clearly and demonstrate future visions to improve their access to funding.

Private investment models, including off-grid technologies like Devergy's in Tanzania and Pay-As-You-Go (PAYG), are making PV solar cells more financially viable in Africa. These models reduce upfront costs for users and have seen significant growth, with Africa accounting for 70% of global off-grid sector investments from 2010 to 2020. Despite challenges, the financial landscape for solar projects in Africa is improving, but further action is needed to address investment difficulties. For instance, crowdfunding is used in Europe to raising small amounts of money from a large number of individuals or organizations and allows individuals to invest in solar projects. It democratizes investment, engages communities, and supports smaller installations. In Europe, funding possibilities for solar installations include:

- Government subsidies and incentives: Many European governments offer subsidies, grants, tax incentives, or feed-in tariffs to support solar installations and encourage renewable energy adoption.
- European Union funding: Programs like Horizon Europe, the European Structural and Investment Funds, and the European Investment Bank (EIB) provide financial support for renewable energy projects, including solar installations.
- Green finance initiatives: Banks and financial institutions in Europe increasingly offer green financing options tailored specifically for renewable energy projects, including solar installations. These may include green loans, green bonds, or specialized investment funds.
- Energy cooperatives and community funding: Community-driven initiatives and energy cooperatives allow individuals or groups to collectively invest in solar installations and share the benefits and risks.
- Corporate and commercial financing: Businesses, industries, and commercial entities may opt for various financing arrangements, such as power purchase agreements (PPAs), leasing, or third-party ownership models, to finance solar installations on their premises.
- Research and innovation grants: Institutions, research organizations, and consortia may receive funding from European Union research programs or other sources to develop innovative solar technologies or improve existing ones.

Several business models have been employed for solar energy in Africa to address diverse needs, market scales and conditions. Here are some prominent business models used for solar energy in Africa, see Table 4.

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Table 4. Business Models for Solar Energy in Africa.

Business Models	Description
Pay-as-You-Go (PAYG)	PAYG allows customers with limited financial resources to pay for solar systems in small, manageable increments. Once the system fully paid, users own it outright.
Solar Home Systems (SHS	SHS are modular installations of solar panels on individual households to provide electricity.
Mini-Grids	They offer a scalable solution that can cater to various energy demands to communities in remote or off-grid areas
Solar Water Pumping	Solar water pumping models involve using solar energy to power water pumps for irrigation and domestic water supply in agriculture-dependent regions. This contributes to increased agricultural productivity and improved access to clean water.
Solar Irrigation	Solar irrigation systems leverage solar energy to power pumps for agricultural irrigation. This model is particularly relevant in regions where reliable access to electricity is limited, and it helps farmers increase crop yields and reduce dependence on rainfall.
Solar Lanterns and Portable Solar Devices	Providing solar lanterns and portable solar devices for lighting and phone charging is a straightforward and affordable model. These devices are often used in areas with limited access to grid electricity and contribute to improved lighting and communication.
Commercial and Industrial Solar Solutions	Businesses and industries in Africa can adopt solar solutions to meet their energy needs. This can involve rooftop solar installations, solar water heating, and other customized solutions to reduce reliance on the grid and lower operational costs.
Results-Based Financing (RBF)	RBF models involve providing financial incentives or subsidies based on the achievement of specific results, such as the installation of a certain number of solar systems or the generation of a predetermined amount of clean energy. RBF encourages the private sector to invest in renewable energy projects.
Community-Based Solar Projects	Community-based models involve the collaborative development and ownership of solar projects by local communities. These projects may range from small-scale solar installations to community mini-grids, fostering community engagement and shared benefits.
Leveraging Carbon Credits	Companies can participate in carbon credit programs, where they earn credits for reducing greenhouse gas emissions by investing in solar projects. These credits can then be sold or traded on the international carbon market, providing additional revenue streams.

The business models for PV grid systems typically include:

- Power Purchase Agreements (PPA): This involves agreements between a developer and a utility company or consumer to purchase the electricity generated by the PV system at a predetermined rate.
- Net Metering: Under this model, the PV system owner is credited for the electricity they generate and feed into the grid, offsetting their electricity consumption from the grid when their system is not generating power.

These models may also incorporate variations such as Feed-in Tariffs (FiT), Feed-in Premiums (FiP), and Auctions within the PPA framework.

4. Technologies Adopted

4.1. Solar Home

4.1.1. Solar Kits Revolutionizing Energy Access in Africa

Solar kits, particularly "Solar Home Systems," play a crucial role in improving access to energy in Africa, especially in rural areas not connected to the electrical grid. These kits, consisting of a solar panel and a battery, provide an independent source of energy that caters to various needs, such as charging mobile phones, lighting, and even powering more energy-demanding devices like televisions or small refrigerators [54]. The table below (Table 5), shows statistics of Solar Kit Sales in Sub-Saharan Africa.

Table 5. Statistics of Solar Kit Sales in Sub-Saharan Africa (First Half of 2018).

solar products sold	Total number of solar products sold	Percentage of sales in sub-Saharan Africa
Solar lamps; "Solar Home System" kits;	1.5 million	40%

4.1.2. Solar Home System (SHS)

For a Solar Home System (SHS), carefully selected features cater to the energy needs of a household. These systems include solar panels with a total capacity of 600 watts, optimized to efficiently capture available solar energy. The integrated battery, with a capacity of 400 Ah, ensures proper storage of energy, guaranteeing a reliable power supply even during periods of low solar intensity. A robust 1.5 kW inverter allows for the conversion of direct current into alternate current, enabling the use of essential household appliances. These SHS encompass direct current appliances such as LED lights, DC fans, and mobile charging points, providing a comprehensive solution for domestic energy needs. Additionally, the system is equipped with a Maximum Power Point Tracking (MPPT) charge controller to optimize the efficiency of solar energy capture.

4.2. Solar Farms

4.2.1. Solar Farms Generation Capacity in Africa

Solar farms are extensive fields of solar panels to harness the abundant sunlight, converting this energy into clean electricity. In addition to providing an environmentally friendly energy source, solar farms contribute to the reduction of greenhouse gas emissions, promoting sustainable development [55]. The expansion of these projects also contributes to the creation of local jobs and the improvement of access to electricity, thereby strengthening energy infrastructure and driving economic progress throughout Africa. Table 6, illustrates major Solar Power Plants in Africa, highlighting the scale and geographical distribution of these crucial initiatives for the continent's energy future.

Table 6. Major Solar Farms in Africa.

Country	Farm Name	Type	Area	Production Capacity
South Africa	-Jasper -Kathu Solar Park	-Photovoltaic -Thermal	• 145 hectares • -240 hectares	• 96MW • 100 MW
Angola	-Quilemba -Baia Farta	-Photovoltaic - Photovoltaic	• -78 hectares	• 45MWp • 96 MW

			• -186 hectares	
Egypt	-Benban -Charm Al-Cheikh	-Photovoltaic -Photovoltaic	1 440 hectares	• 1.650 MW • 5 MW/day
Botswana	in the process of being launched	Thermodynamic	in the process of being launched	200 MW
Ivory Coast	Boundiali	Photovoltaic		37.5 MW

4.2.2. Decentralized Energy Generation

Solar farms are installations composed of photovoltaic modules, inverters, power conditioning units, and grid connection equipment. Designed to generate electricity from solar energy, these farms are typically owned by utility companies striving to provide electricity within their service areas. The illustration below depicts an example of a solar farm, highlighting the process of transmitting energy to households.

Within the solar panels are multiple photovoltaic modules that directly convert solar energy into electricity. This electricity is then injected into the electrical grid. An intriguing aspect of solar farms is their decentralized nature, meaning they are usually located near consumption areas rather than having a larger central facility in a different region with transmission across the national grid. This approach offers notable advantages, including the reduction of energy losses associated with long-distance transmission.

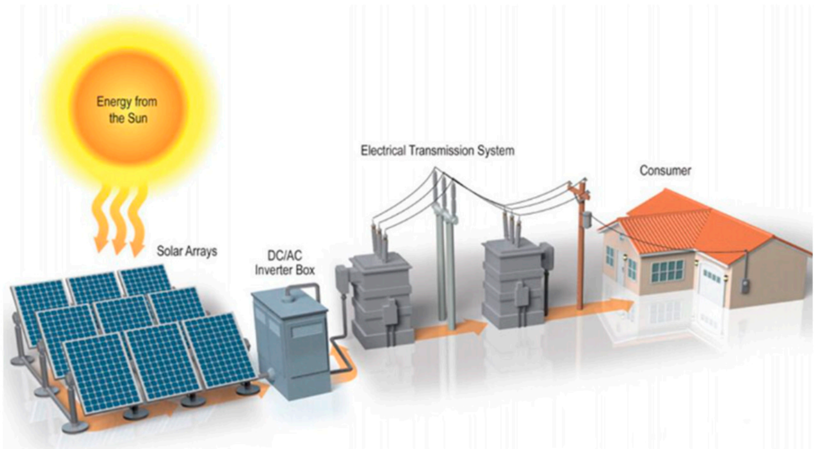

Figure 11. Diagrammatic Representation of a Solar Farm.

4.3. Mini-Grids, Off-Grid

4.3.1. Mini-Grids, Off-Grid Generation Capacity in Africa

Mini-grids, or mini-electricity networks, play a vital role in improving access to electricity in Africa, especially in remote regions where connection to the main grid is often challenging. These mini-grids can be powered by renewable, thermal, or hybrid energy sources, providing a sustainable and independent solution. However, despite their social and technological relevance, mini-grids in Africa face economic, commercial, and regulatory challenges that hinder their development without adequate financial support [56].

Table 7 outlines some international initiatives and funds aimed at supporting "off-grid" projects in Africa, including mini-grids, to overcome the specific obstacles in the region:

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La Figure 12 provides a graphical representation of off-grid solar generation capacity in Africa. This illustration highlights the distribution and extent of off-grid solar energy production capacity across the continent.

Table 7. International Initiatives and Funds Supporting Off-Grid Electricity Projects in Africa.

Initiative/Fund	Objective	Amount
Off Grid Access Fund (OGEF)	Facilitate access to off-grid energy	$58 million
Results-Based Off-Grid Electrification Program (ROGEP, World Bank)	Off-grid electrification projects	$150 million
Energos Program (European Union)	Deployment of independent networks	$117 million
Millennium Challenge Corporation (MCC)	Financing off-grid electrification and mini-grids for poverty reduction	Varies by country, e.g., $32 million in Benin
Essor A2E Program (DFID)	Support for solar projects with independent networks	
Direct Loans (African Development Bank)	Financing specific Solar Home Systems projects	$28 million

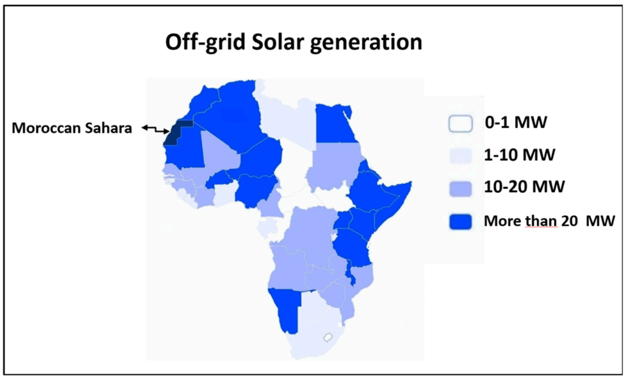

Figure 12. Off-grid Solar Generation Capacity in Africa.

4.3.2. The Functioning of Photovoltaic Mini-Grid Systems

A mini-grid system operates on the principle of decentralized production and distribution of electricity. In the case of a mini-grid with a photovoltaic source, photovoltaic solar panels are installed to capture solar energy and convert it into continuous electricity. These panels are connected to a charge controller, which regulates the flow of energy between the solar panels and the battery.

The battery plays a crucial role by storing the electricity generated by the solar panels (see Figure 13). This allows the system to provide electricity even during periods without sunlight, ensuring a stable and continuous power supply. A remote monitoring device is often integrated to monitor the system's performance, enabling efficient management and early detection of any issues.

In case of adverse weather conditions or high electricity demand, a diesel generator can be activated as a backup power source. This ensures the continuity of the power supply, maintaining operational reliability.

Thus, the mini-grid system with a photovoltaic source operates to maximize the utilization of solar energy, store excess energy in a battery, and incorporate backup mechanisms to ensure a stable power supply, contributing to reliable and sustainable electricity distribution in decentralized areas.

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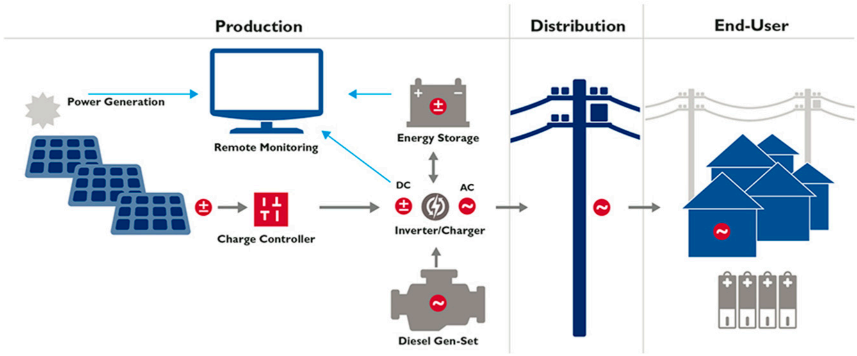

Figure 13. Mini-grid system.

4.4. Irrigation

Solar irrigation, harnessing the energy of the sun to power pumps, emerges as an innovative and sustainable solution to meet the water needs of agriculture. A significant example of this approach is the range of solar pumps from Futurepump, specially designed for small-scale farms. This system relies on a simple process, starting with the installation of photovoltaic solar panels that convert solar energy into electricity. This electricity then powers the solar pumps, allowing the pumping of water from sources such as wells, rivers, or reservoirs, and transporting it to agricultural areas for crop irrigation.

Egypt, heavily dependent on the Nile for its water supply, has witnessed a modernization of its irrigation systems. The integration of electric pumps and more efficient irrigation techniques reflects this evolution, aiming to maximize water use while meeting agricultural needs [57].

In Morocco, the use of groundwater for irrigation is a common practice, although sustainable management of this resource remains a significant concern. Farmers rely on various techniques, highlighting the diversity of approaches in different regional contexts.

Table 8 provides an overview of various solar irrigation techniques in Africa, highlighting their distinct characteristics, advantages, and associated challenges. The choice of techniques often depends on local conditions, available resources, and farmer preferences.

Table 8. Solar Irrigation Techniques in Africa.

Solar Irrigation Technique	Description	Advantages	Challenges
Surface Solar Pumps	Utilizes solar pumps to draw water from surface sources (rivers, reservoirs) and transport it to fields.	- Free solar energy utilization. - Suitable for small-scale farms.	- Dependency on weather conditions (sunshine). - Requires storage batteries for continuous night time use.
Submersible Solar Pumps	Installs solar submersible pumps directly in wells or reservoirs, lifting water for irrigation.	- Reduction in costs associated with surface structures. - Efficient use of solar energy.	- Higher initial costs. - Requires technical skills for installation and maintenance.
Solar Drip Irrigation Systems	Combines solar pumps with drip irrigation systems, providing precise	- Water savings through precise distribution. -	- Initial costs. - Regular maintenance of drippers required.

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	and economical water distribution.	Suitable for intensive cropping.	
Solar Central Pivot Irrigation	Uses solar energy to power central pivot systems, irrigating crops in a circular pattern.	- Extensive field coverage. - Automation of the irrigation process.	- High initial investment. - Requires space for central pivot deployment.

4.5. Solar Lighting

4.5.1. Solar Lighting in Africa

Solar lighting in Africa is emerging as a transformative solution to address energy access challenges on the continent. With vast regions experiencing limited access to reliable electricity, especially in rural areas, solar lighting offers a sustainable and decentralized alternative. Solar-powered lights harness the abundant sunlight available in many African countries, converting it into electricity through photovoltaic cells [58]. These lights are particularly valuable in off-grid communities, providing illumination for homes, schools, and public spaces during the evening hours. Beyond enhancing safety and security, solar lighting contributes to improved educational opportunities by enabling students to study after dark. Additionally, it has positive implications for economic activities, allowing businesses to extend their operating hours. The adoption of solar lighting not only reduces dependence on traditional energy sources but also contributes to environmental sustainability, aligning with the broader global effort to promote clean and renewable energy solutions [59].

This table (Table 9) presents a variety of solar lighting technologies in Africa, highlighting their features, advantages, and specific challenges.

Table 9. Solar Lighting Technologies in Africa.

Solar Lighting Technology	Description	Advantages	Challenges
Traditional Solar Streetlights	Use of standalone streetlights equipped with solar panels and batteries to illuminate streets and public spaces.	- Simple and quick installation. - Long-term energy cost reduction.	- Requires regular maintenance. - Vulnerable to vandalism.
Portable Solar Lanterns	Small individual lamps powered by solar panels, often used for domestic lighting.	- Easy to use and transport. - Affordable solution for off-grid areas.	- Limited storage capacity. - Battery lifespan.
Solar LED Lighting Systems	Utilization of solar-powered LED light sources, offering an eco-friendly alternative.	- High luminous efficiency. - Long lifespan of LEDs.	- Initial costs for quality equipment. - Requires adequate solar exposure.
Smart Solar Public Lighting Systems	Integration of sensors and intelligent technologies to automatically regulate lighting	- Energy savings through smart regulation. - Reduction in carbon emissions.	- Higher initial investments. - Need for technical skills for maintenance.

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	based on environmental conditions.		

4.5.2. Solar Street Lighting System

For solar-powered public lighting, the specifications could include solar panels with a total capacity of 300 watts installed atop lampposts, capturing sufficient solar energy during the day. Each lamppost would be equipped with a battery with a capacity of 200 Ah to store solar energy, ensuring a reliable power supply during the night. The streetlights would feature high-efficiency LED bulbs, each with a power rating of 20 watts, ensuring adequate illumination while maximizing the use of stored energy. Additionally, an intelligent charge controller would be integrated to regulate the flow of energy between the solar panels and the battery, ensuring optimal charging and extending the battery's lifespan. These specifications are adaptable based on the specific requirements of each project, providing a customized and efficient solar public lighting solution.

Haut du formulaire

4.6. Tools

There are several open-source and free tools available for the design and assessment of solar installations. These tools can be valuable for professionals, researchers, and enthusiasts working on solar projects in Africa. Here's a table (Table 10) of some widely used tools [60].

The article and database by Sebastian Sterl provide a detailed evaluation of Africa's solar potential, identifying optimal locations for photovoltaic and wind solar parks. Their analysis facilitates energy planning by highlighting opportunities and challenges related to resource quality and network proximity. This resource is crucial for decision-makers and stakeholders aiming to maximize Africa's solar capacity and promote a sustainable energy transition [61].

Table 10. Exploring Solar Energy Software Solutions.

Software	Description
PVWatts	Developed by the National Renewable Energy Laboratory (NREL), PVWatts is a widely used tool for estimating the energy production of grid-connected solar photovoltaic (PV) systems. It allows users to assess the performance of solar installations based on various parameters.
HOMER	HOMER Legacy is a simulation software for designing and optimizing microgrid systems. It can be used to assess the feasibility and economic viability of solar installations, particularly in off-grid or remote areas.
SAM	Also developed by NREL, SAM (System Advisor Model) is a comprehensive performance and financial model designed to facilitate decision-making for project developers and investors. It covers various renewable energy technologies, including solar.
OpenStreetMap	OpenStreetMap is a collaborative mapping platform that can be used for site assessment and mapping. Various solar-related data layers, such as sunlight exposure and terrain data, can be added for project planning.
QGIS	Quantum GIS QGIS is an open-source Geographic Information System (GIS) that allows users to analyse and visualize spatial data. It can be useful for solar site selection and geospatial analysis related to solar projects.
RETScreen	RETScreen is a clean energy project analysis software developed by the Government of Canada. It includes tools for assessing the performance, costs, and benefits of renewable energy and energy efficiency projects, including solar.

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Energy3D	Energy3D is a simulation-based design tool for renewable energy systems, including solar PV installations. It provides a 3D environment for modelling and assessing the performance of solar projects.
PVSyst	PVSyst is a widely used software for modelling, simulation, and analysis of solar photovoltaic systems. While the full version is commercial, PVSyst offers a free version with limited capabilities that can still be useful for small-scale projects.
HelioScope	HelioScope a solar design and sales platform that allows users to model and design solar PV installations. It offers both free and premium versions, with the free version providing basic functionality for solar design.
OpenSolar	OpenSolar is a cloud-based platform for solar design and project management. It offers free access to its design tool, allowing users to create solar designs and assess the performance of solar installations.
PVGIS	PVGIS is an online platform that offers solar radiation and temperature data, allowing users to estimate the performance of photovoltaic systems. It provides information on the solar energy potential for various technologies, including fixed and tracking systems.

4.7. Green Hydrogen

Green hydrogen represents a clean and renewable energy source, produced exclusively from renewable energy sources such as wind, solar, or hydropower. Its production without greenhouse gas emissions makes it an essential "green" resource in the transition to a low-carbon economy. In Africa, the growing interest in green hydrogen can be attributed to several factors. Firstly, the continent has immense solar and wind potential, providing ideal conditions for the competitive production of green hydrogen. The economic and environmental benefits of this energy transition also prompt the commitment of African governments and industrial players. Strategic agreements with international partners and massive investments in projects like the Aman project in Mauritania (see Table 11) or initiatives in Namibia demonstrate Africa's ambition to play a key role in global green hydrogen production.

Table 11. key green hydrogen initiatives in Africa.

Country	Description
Mauritania	Mauritania has signed a $40 billion framework agreement with CWP Global for the Aman project, including 18 GW of wind and 12 GWp of solar. The project aims to become a global benchmark for green hydrogen.
Namibia	Namibia has approved a $10 billion project with Hyphen Hydrogen Energy to produce 2 million tons of green ammonia per year. The cost of green hydrogen production is estimated at $1.5/kg.
Morocco	Morocco, with its Noor Ouarzazate complex, aspires to become a global leader in green hydrogen. Strategic partnerships with OCP and UM6P aim to industrialize green ammonia production.
South Africa	South Africa is exploring opportunities for green hydrogen production. Projects are in planning, capitalizing on the country's solar and wind capacity.
Egypt	Egypt is assessing possibilities for green hydrogen production, exploring the benefits of solar energy to stimulate low-carbon economic growth.

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5. Stakeholders and Players

5.1. Companies

The solar industry in Africa relies on a variety of suppliers for solar infrastructure, including solar panels, inverters, mounting structures, and other components. The key suppliers can vary depending on the specific needs and scale of the projects. here are some key suppliers that have been active in providing solar infrastructure in Africa:

Table 12. Leading Solar Industry Suppliers in Africa.

Company	Description
Trina Solar	Trina Solar is a leading global provider of solar panels and has been involved in supplying solar modules for projects worldwide, including in Africa.
JinkoSolar	JinkoSolar is one of the largest and most prominent solar panel manufacturers globally, supplying solar modules for utility-scale projects.
Canadian Solar	A major supplier of solar panels and has a significant presence in the global solar market, including projects in Africa.
Huawei	Huawei is a well-known supplier of solar inverters and has been involved in providing inverter solutions for large-scale solar projects.
ABB	ABB is a multinational company that offers a range of power and automation technologies, including solar inverters used in photovoltaic systems.
SMA Solar Technology	SMA is a German company specializing in solar inverters and has been involved in supplying inverters for various solar projects.
Nextracker	Nextracker provides advanced solar tracker systems and has been involved in utility-scale solar projects globally.
Array Technologies	Array Technologies is a leading provider of solar tracking systems, contributing to the efficiency of solar farms.
Schletter Group	Schletter offers mounting structures for solar installations, including ground-mounted and rooftop systems.
Tesla (Powerwall)	While primarily known for electric vehicles, Tesla's Powerwall has been used for residential energy storage solutions, contributing to off-grid and hybrid systems in some parts of Africa.
BYD	BYD is a Chinese company that manufactures energy storage solutions, including lithium-ion batteries used in solar applications.
Schneider Electric	Schneider Electric provides energy storage solutions and has been involved in projects that integrate solar with storage for reliable power supply.
Engie	Engie, a global energy company based in France, has been involved in renewable energy projects across Africa, including solar installations. The company is known for its participation in utility-scale solar projects and has a presence in multiple African countries.
EDF Renewables	EDF Renewables, a subsidiary of Électricité de France (EDF), is engaged in the development and operation of renewable energy projects, including solar, in various regions, including Africa. The company has been active in the development of solar projects in several African countries.
TotalEnergies	A major French energy company, has diversified its portfolio to include renewable energy. The company has shown interest in solar projects in Africa, focusing on both utility-scale and distributed solar solutions.
Vergnet Group	Vergnet Group, a French company specializing in renewable energy and water solutions, has been involved in the development and installation of solar projects in Africa. They provide a range of renewable energy solutions, including solar hybrid systems.

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Cap Vert Energie	Cap Vert Energie, a French independent producer of renewable energy, has been active in developing solar projects in Africa. The company focuses on decentralized energy solutions and has experience in off-grid and mini-grid projects.
Ciel et Terre	Ciel et Terre, a French company specializing in floating solar solutions, has been involved in projects globally, including Africa. Their floating solar technology is designed for applications such as reservoirs and lakes.
Schneider Electric	Schneider Electric, while a global company, has a significant presence in France. It provides energy management and automation solutions, including those related to solar energy. Schneider Electric has been involved in solar projects aimed at improving energy access and efficiency in Africa.

5.2. NGOs

There are several non-governmental organizations (NGOs) that are actively involved in promoting and implementing solar energy projects in Africa.

Table 13. Organizations Promoting Solar Energy Solutions for Rural Electrification in Africa.

Organization	Description
Barefoot College	Based in India, works globally to empower rural communities by providing education and training, including in solar electrification. They have implemented solar projects in various African countries.
Electriciens sans frontières (Electricians Without Borders)	French NGO that works to provide access to electricity in remote and vulnerable areas. They engage in electrification projects, including the use of solar energy, in various African countries.
Energy 4 Impact	An NGO that focuses on promoting renewable energy solutions, including solar, to improve energy access in rural and off-grid areas of Africa.
Energy Assistance	Energy Assistance, or Électriciens sans frontières Belgium, has a branch in France. The organization focuses on providing sustainable energy solutions, including solar power, to communities in need.
Geres (Group for the Environment, Renewable Energy, and Solidarity)	A French NGO that works on sustainable development projects, including renewable energy initiatives in Africa. They have been involved in promoting solar energy for rural electrification.
Green Energy Africa	An NGO that focuses on promoting sustainable and renewable energy solutions in rural areas of Africa. They work on solar electrification projects to improve energy access.
GIZ	This German agency is very active and present all over the world and produce specific reports on local business environment in particular for solar energy in Africa https://www.giz.de/en/worldwide/africa.html
HEDON (UK/Netherlands)	The Household Energy Network (HEDON) operates in the UK and the Netherlands and focuses on promoting sustainable energy solutions for households, including solar, in various regions, including Africa.
Hydraulique sans Frontières (Hydraulics Without Borders)	A French NGO dedicated to providing access to water and energy. While their primary focus is on water projects, they may be involved in energy projects, including solar, in certain regions.
Initiative Développement	A French NGO working on various development projects, including those related to energy access in Africa. They may be involved in promoting solar solutions for rural communities.

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(Development Initiative)	
Power for All	A global campaign that advocates for universal energy access. While not an NGO in the traditional sense, they collaborate with NGOs, businesses, and governments to promote decentralized renewable energy solutions, including solar, in Africa.
Practical Action (United Kingdom)	An international development organization that promotes the use of technology to address global challenges. They work on renewable energy projects, including solar, in several African countries
RAC-France (Réseau Action Climat - France)	Part of the Climate Action Network (Réseau Action Climat), a network of NGOs working on climate-related issues. While not exclusively focused on solar, they may engage in projects promoting renewable energy in the context of climate action.
Renewable Energy and Energy Efficiency Partnership (REEEP)	An international organization that works to accelerate the market-based deployment of renewable energy and energy efficiency. They collaborate with governments, businesses, and NGOs in Africa and beyond.
Renewable World (United Kingdom)	A UK-based charity that focuses on providing renewable energy solutions, including solar, to improve the lives of people in poverty. They work in various countries, including some in Africa.
Rural Electrification Club (REC) Foundation (Italy)	Based in Italy, works on rural electrification projects, including the deployment of solar energy solutions, to improve energy access in remote areas of Africa.
SELCO Foundation	Although primarily focused on India, SELCO Foundation has been involved in projects across Africa. They work to enhance sustainable energy access through innovations, capacity building, and community engagement.
SOLARKIOSK AG (Germany)	A Germany-based social enterprise that aims to provide clean energy solutions, including solar, to off-grid and underserved communities in various parts of Africa.
Sunrise (Sweden)	A Swedish NGO that works to bring solar energy solutions to rural and off-grid areas in Africa. They focus on empowering communities through sustainable energy access.
We Care Solar (Netherlands)	Based in the Netherlands, focuses on providing solar energy solutions for healthcare facilities in developing countries, including parts of Africa, to improve medical services.
Wind Empowerment (European Network)	A European network that focuses on promoting small-scale wind and solar energy solutions, particularly for rural electrification in developing countries, including African nations.
World Wide Fund for Nature (WWF)	A global conservation organization involved in promoting sustainable energy solutions, including solar, in Africa to address climate change and environmental sustainability.

5.3. R&D

Table 14. Research and Development Initiatives in the Renewable Energy Sector.

Program/Project	Organization/Initiative
Africa Clean Energy Corridor	IRENA
Africa Solar Development Program	World Bank
Africa Union-EU Renewable Energy Cooperation Programme	AU-EU
African Bioenergy Policy Framework and Guidelines	AU

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African Renewable Energy and Access Program	AU
African Renewable Energy	AU
Initiative (AREI)	AU
Burkina Faso Electricity Sector Support	World Bank
Electrification Financing Initiative	EU
European Research Area Network for Smart Energy Systems	EU
European Investment Bank (EIB) Solar Projects in Africa	EU
European Union's Electromobility in Emerging Economies (E-Mobility Plus) Project:	EU
Power Africa	US
Kenya Off-Grid Solar Access Project	World Bank
Madagascar Power Sector Support Project	World Bank
Millennium Challenge Corporation (MCC) Compact Programs:	US
NDC Support Program for Renewable Energy in Africa	IREN
Niger Solar Electricity Access Project	World Bank
Nordic Climate Facility (NCF) Projects	Nordic Development Fund
Off-Grid Energy Access Fund	AfDB
Scaling Solar Program	World Bank Group
U.S. African Development Foundation (USADF) Off-Grid Energy Challenge:	US
U.S. Trade and Development Agency (USTDA) Grants	US

6. Discussion and Conclusion

The solar business in Africa offers several benefits to international companies that engage in the development, implementation, and promotion of solar energy solutions. Here are key ways in which international companies can benefit:

- **Market Expansion and Growth Opportunities:** Africa presents a rapidly growing market for solar energy solutions due to increasing energy demand, a growing population, and a need for electrification in rural areas. International companies can capitalize on these opportunities to expand their market reach and achieve business growth [62].
- **Diversification of Investment Portfolio:** Investing in Africa's solar market allows international companies to diversify their investment portfolios. The renewable energy sector, particularly solar, provides a sustainable and environmentally friendly option, aligning with global trends toward clean energy and sustainability.
- **Corporate Social Responsibility (CSR) Impact:** Engaging in solar projects in Africa allows international companies to demonstrate corporate social responsibility by contributing to sustainable development, addressing energy poverty, and promoting environmental stewardship. These initiatives can enhance the company's reputation and brand image.
- **Technology Transfer and Innovation:** International companies can contribute to technology transfer and innovation by bringing advanced solar technologies, expertise, and best practices to the African market. Collaborations with local stakeholders foster knowledge exchange and drive innovation in the renewable energy sector.
- **Government Incentives and Partnerships:** Many African governments are actively promoting renewable energy projects, offering incentives, and seeking partnerships with international companies. These collaborations can lead to favourable regulatory environments, financial support, and joint ventures, facilitating the implementation of solar projects.
- **Job Creation and Capacity Building:** International companies engaging in solar projects in Africa contribute to job creation and capacity building. By employing local talent, providing training programs, and transferring skills, these companies strengthen the workforce and support economic development in the regions where they operate.

- **Innovative Business Models:** The African market provides an opportunity for international companies to develop and implement innovative business models, such as pay-as-you-go (PAYG) financing, to make solar solutions more accessible to a broader population. Such models can be adapted to local needs and conditions.
- **Access to New Customers and Markets:** Engaging in the solar business in Africa provides international companies with access to new customers and markets. This is particularly relevant as solar solutions become integral to addressing energy challenges and achieving sustainable development goals on the continent.
- **Risk Diversification:** International companies can diversify their business risks by operating in multiple geographical regions. While there are challenges, including political and regulatory uncertainties, the potential benefits of tapping into Africa's solar market can outweigh these risks with careful planning and strategic partnerships.

Africa is on the one hand often presented as a continent of great resources, herein related to solar power, and the other hand, millions of African lack basic needs, herein related to electricity which is vital for livability. In the current situation, African solar power is mainly driven by international bodies and relies on their studies, reports, market analysis, business models, equipment, funding and technical tools for design, assessment, planning… However, despite this huge concern, the real impacts and benefits on local population is not well identified or measured and many solar installations have been either stopped due to lack of maintenance (mainly off-grid ones) or have shown to be more expensive in capital and operation than expected (mainly CSP ones which also consume a rare water resource – e.g., water consumption for the Ouarzazate Noor complex is estimated at 2.5 to 3 million m^3/year ! [63]).

As solar is recognized to be a competitive and profitable technology, African countries should consider:

- Building pan-African consortia to produce the main components of solar photovoltaics (PV, inverters, MPPTs, batteries, Metering supervision apps…). In fact, the technology is known and the competences are available if put in common. Moreover, this will ensure maintenance requirements for long term usage.
- Promoting inclusive installations by involving citizen and making them prosumers.
- Increasing local skills by delivering specific learning curricula in national or regional solar centers.
- Implementing African research programs to develop specific tools and components as well as for raising awareness of decision-makers and end-users to adopt and implement specific circular financial instruments.

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