ELSEVIER

Possibility of solar thermal power generation technologies in Nigeria: Challenges and policy directions

Daniel Akinyele[a,*], Olubayo Babatunde[a], Chukwuka Monyei[b,g], Lanre Olatomiwa[c], Adebunmi Okediji[d], Desmond Ighravwe[e], Onile Abiodun[d], Mobolaji Onasanya[f] and Kehinde Temikotan[d]

[a] Department of Electrical and Electronics Engineering, University of Lagos, Nigeria
[b] Gidia Oaks Centre for Energy Research, Lagos, Nigeria
[c] Department of Electrical and Electronics Engineering, Federal University of Technology, Minna, Nigeria
[d] Faculty of Engineering, Elizade University, Ilara-Mokin, Ondo State, Nigeria
[e] Department of Mechanical and Biomedical Engineering, Bells University of Technology, Ota, Nigeria
[f] Department of Electrical and Electronics Engineering, Yaba College of Technology, Lagos, Nigeria
[g] Centre for Enterprise, Innovation and Entrepreneurship, University of the West of England, UK

This paper presents a brief overview of solar thermal power generation technologies (parabolic trough, central tower receiver, linear Fresnel reflecting and parabolic dish concentrators) and their possible application in Nigeria. It further discusses an array of barriers to the development of the technologies, such as the lack of understanding of solar thermal systems, lack of incentives for renewable technologies and previous experience of solar photovoltaic systems failure that is making people doubt the viability of renewable electricity. Other barriers that were considered are lack of technical expertise, high technology cost and lack of project funding, including a lack of enabling policies to drive the technologies. This study then develops a policy framework that will help to understand and address some of the identified challenges to achieve widespread adoption, application, and diffusion in Nigeria. In addition, the framework will provide useful insights into the major issues that affect community-based or regional solar thermal power systems in developing countries. Widespread application of these clean energy technologies can help mitigate climate change.

Introduction

The application of renewable energy technologies for electricity production continues to be an important agendum of governments, decision-makers, energy planners and other relevant stakeholders around the globe [1,2]. Solar thermal system, which is one of these technologies, produces electricity from the sun through a thermodynamic process [3]. This system has been explored and developed in many parts of the world, for instance in some developed countries [3]. With this achievement, solar thermal is believed to have the potential to thrive in developing countries where there are huge solar energy resources.

In recent times, solar photovoltaic (PV) power systems have witnessed a widespread application of on-grid and off-grid energy systems in several countries around the world, due to the gradual reduction in PV modules cost and the ease of installation compared to the other energy technologies [2]. Energy is currently being supplied to several remote communities through the solar PV technology, especially in villages within sub-Saharan Africa region that possess appreciable solar energy resources. However, the issue of system failure is one of the major challenges that affect the proliferation of solar PV energy systems in several parts of the region, using Nigeria's situation as an example [4]. The lack of

*Corresponding author Akinyele, D. (dakinyele@unilag.edu.ng, akinyelescholar@gmail.com)

1755-0084/ https://doi.org/10.1016/j.ref.2019.02.002

standard design and installation procedure has been identified as a major cause of this setback. To address this problem, researchers advocate the use of standard materials and deployment procedure in practice [4,5], while making a case for other solar technologies that can serve as an enabling alternative. This has motivated the interest in solar thermal power systems deployment in Nigeria. It is against this backdrop that the current study discusses the possibility of solar thermal power generation technologies in Nigeria, its associated challenges and policy initiatives.

Between 2006 and 2016, the concentrating solar thermal power global capacity was 4.9 GW [1]. A bulk of this capacity was achieved in Spain and the United States, compared to the rest of the world. Table 1 shows the solar thermal systems in different countries around the world. The huge solar energy potential in Nigeria can make the solar thermal power generation system a promising electricity option for addressing the energy shortage problem in the country. However, the lack of policy to drive this energy option limits its application in Nigeria; this problem is among the main issues the current study considers. Currently, several contributions have been made to address different aspects of this technology application, some of which forms a background for this section.

Some of these contributions have considered the simulation and analysis of concentrated and hybrid solar thermal power [6,7]. A study has discussed the technical and economic potential of concentrating solar thermal power generation [8]. A review paper has also been published focusing on how to enhance solar thermal systems efficiency using their thermo-physical properties [9]. In addition, the techno-economic analysis of solar thermal energy production and application has been discussed, which was used to improve the production of chilled water for agricultural soil cooling [10]. A study on the non-tracking concentrating collector for solar thermal applications has been presented using South-East Asia as a test case [11].

Furthermore, a study has been discussed that presents the cost analysis of solar thermal power generator based on the parabolic dish and micro-gas turbine [12], while a high-performance solar thermo-electric system was presented using the combined heat and power [13]. The feasibility and parametric evaluation of hybrid concentrated photovoltaic-thermoelectric system has also been presented [14]. These research works have focused on the design and performance analyses of solar thermal power systems, while other studies consider a review of the various technologies. One of such papers is a review of solar thermal power production technologies [15]. Another study presented the review of the state-of-the-art of solar thermal power plants, with emphasis on the solar concentrator technologies (parabolic trough, parabolic dish and central power tower, and their cost comparison) [16]. The advances in solar power technologies have also been discussed [17].

A review of existing studies on central receiver solar thermal power plants has been presented [18], while the review and the design methodology of concentrated solar power plants were also discussed [19]. Another study has considered the review of the thermodynamic performance evaluation of solar thermal power generation systems [20]. Similarly, a review was presented on the performance enhancement of solar collectors [21]. Furthermore, a study has discussed the progress and latest developments of evacuated tube solar collector, focusing on water heating, heat engines, air conditioning, swimming pool heating, solar cooker, steam generation and solar drying applications for household and industrial sectors [22]. A review of solar power technologies was presented suggesting the modality for sustainable electricity generation [23], while the review paper in Ref. [24] focuses on solar PV-based heat and power generation systems, including solar PV and solar flat collectors have been discussed [24].

A review of solar thermal facades analysis has been discussed [25]. The design of a distributed stand-alone solar thermal co-generation plant has been reported for an isolated region in Egypt [26], while the review of concentrating solar power plants and new developments in high-temperature thermal energy storage technologies was also presented [27]. Similarly, additional works have considered thermal storage concept for solar thermal power plants. One of these studies laid emphasis on direct steam generation [28], while another work focuses on the direct steam generation in parabolic trough collectors [29]. Other contributions are on the review of thermodynamic optimization and modeling of the solar thermal Brayton cycle [30], and the review of various thermodynamic cycles for high-temperature power generation systems [31].

A review of an integrated combined-cycle system driven by a solar tower has been presented. The work presented the barriers to the development of the technology [32]. The study in Ref. [33] used an analytical hierarchy process to identify the best solar thermal collection technology for electricity generation in north-west India. The innovation in concentrated solar power has been discussed [34], while the integrated solar combined cycle (ISCC) power plants were presented in Ref. [35]. A review of high-temperature central receiver design has been discussed focusing on the application of concentrating solar power system [36].

The mentioned papers presented quality research and relevant account of the solar thermal power generation systems; they provided appropriate background knowledge for the current paper. Some of the mentioned papers have focused on the optimisation and improvement of the thermodynamic process of the solar thermal system, while some of them have also discussed the overview of the solar thermal technologies, such as the linear concentrating technology (e.g. parabolic troughs and Fresnel reflectors), solar power tower and solar engine technologies, for electricity production.

This study, however, takes a different dimension. It does not only present an overview of the solar thermal technologies and applications but also discusses the major barriers to their adoption in developing countries, using Nigeria as a case study. Some of these barriers include lack of understanding of the technologies, policy inconsistency and agency conflicts, lack of enabling laws and targets for solar thermal capacity expansion and non-implementation of Electric Power System Reform (EPSR) Act on rural electrification fund. This study also found that the lack of incentives for renewable energy technologies, lack of technical expertise, high technology cost and lack of funding are among the barriers that affect the solar thermal technology adoption and implementation, including the previous experience of solar PV systems failure in several communities that makes the people lose confidence in the viability of renewable technologies in the country.

TABLE 1

Solar thermal power stations in different parts of the world [37].

Capacity (MW)	Name	Country	Location	Type of Technology	Comment
636	Archimede combined cycle power plant	Italy	Syracuse, Sicily	ISCC with parabolic trough	Combined cycle station commissioned in 2003, and the solar field commissioned in 2010
472	Ain Beni Mathar Integrated Thermo Solar Combined Cycle Power Plant	Morocco	Ain Bni Mathar	ISCC with parabolic trough	Completed in 2011
467	Yazd integrated solar combined cycle power station	Iran	Yazd	ISCC with parabolic trough	Became operational in 2009, and in 2011 as a solar integrated plan
392	Ivanpah Solar Power Facility	USA	San Bernardino County, California	Solar power tower	Completed on 13th February, 2014
361	Solar Energy Generating Systems (SEGS)	USA	Mojave Desert, California	Parabolic trough	Commissioned in 1984
280	Mojave Solar Project	USA	Barstow, California	Parabolic trough	Completed in December 2014.
280	Solana Generating Station	USA	Gila Bend, Arizona	Parabolic trough	Completed in October 2013
280	Genesis Solar Energy Project	USA	Blythe, California	Parabolic trough	Commissioned on 24th April, 2014
200	Solaben Solar Power Station	Spain	Logrosán	Parabolic trough	Solaben 3 completed in June 2012, Solaben 2 completed in October 2012, Solaben 1 and 6 completed in September 2013
(Noor I) 200 MW (Noor II) 150 MW (Noor III)	Ouarzazate Solar Power Station	Morocco	Ghassate, Ouarzazate Province	Parabolic trough with 3 h heat storage	Commissioned in February 2016
155	Hassi R'Mel integrated solar combined cycle power station	Algeria	Hassi R'Mel	ISCC with parabolic trough	Production of electricity started in June 2011
150	Solnova Solar Power Station	Spain	Sanlúcar la Mayor	Parabolic trough	Solnova 4 completed in August 2010
150	Andasol solar power station	Spain	Guadix	Parabolic trough	Completed: Andasol 1 completed in 2008, Andasol 2 completed in (2009), Andasol 3 completed in 2011
150	Extresol Solar Power Station	Spain	Torre de Miguel Sesmero	Parabolic trough	Extresol 1 and 2 completed in 2010, Extresol 3 completed in 2012
125	Crescent Dunes Solar Energy Project	USA	Nye County, Nevada	Solar power tower with 10 h heat storage	commercial operation began in September 2015
125	Dhursar	India	Dhursar, Jaisalmer district	Fresnel reflector	Completed in November 2014
100	KaXu Solar One	South Africa	Pofadder, Northern Cape	Parabolic trough	officially commissioned in March 2015
100	Manchasol Power Station	Spain	Alcázar de San Juan	Parabolic trough	Manchasol 1 and 2 completed in 2011
100	Valle Solar Power Station	Spain	San José del Valle	Parabolic trough	Completed in December 2011
100	Helioenergy Solar Power Station	Spain	Écija	Parabolic trough	Helioenergy 1 completed in September 2011, Helioenergy 2 completed in January 2012
100	Aste Solar Power Station	Spain	Alcázar de San Juan	Parabolic trough	Aste 1 A Completed in January 2012, Aste 1B Completed in January 2012
100	Solacor Solar Power Station	Spain	El Carpio	Parabolic trough	Solacor 1 completed in February 2012, Solacor 2 completed in March 2012
100	Helios Solar Power Station	Spain	Puerto Lápice	Parabolic trough	Helios 1 completed in May 2012, Helios 2 completed in August 2012
100	Shams solar power station	UAE	Abu Dhabi Madinat Zayed	Parabolic trough	Shams 1 completed in March 2013
100	Termosol Solar Power Station	Spain	Navalvillar de Pela	Parabolic trough	Termosol 1 and 2 completed in 2013
100	Palma del Río I & II	Spain	Palma del Río	Parabolic trough	Palma del Rio 2 completed in December 2010
75	Martin Next Generation Solar Energy Center	USA	Indiantown, Florida	ISCC with parabolic trough	Completed in December 2010
75	Nevada Solar One	USA	Boulder City, Nevada	Parabolic trough	Operational since 2007
50	Guzmán	Spain	Palma del Río	Parabolic trough	Completed in July 2012
50	Khi Solar One	South Africa	Upington	Solar power tower	Completed in February 2016
50	Bokpoort	South Africa	Groblershoop	Parabolic trough	Commissioned in November 2015
50	Puertollano Solar Thermal Power Plant	Spain	Puertollano, Ciudad Real	Parabolic trough	Completed in May 2009
50	Alvarado I	Spain	Badajoz	Parabolic trough	Completed in July 2009
50	La Florida	Spain	Alvarado (Badajoz)	Parabolic trough	Completed in July 2010
50	Arenales PS	Spain	Morón de la Frontera (Seville)	parabolic trough	Started production in 2013

TABLE 1 (*Continued*)

Capacity (MW)	Name	Country	Location	Type of Technology	Comment
50	Casablanca	Spain	Talarrubias	Parabolic trough	Started production in 2013
50	Majadas de Tiétar	Spain	Caceres	Parabolic trough	Completed in August 2010
50	La Dehesa	Spain	La Garrovilla (Badajoz)	parabolic trough	Completed in November 2010
50	Lebrija-1	Spain	Lebrija	Parabolic trough	Completed in July 2011
50	Astexol 2	Spain	Badajoz	Parabolic trough	Completed in November 2011
50	Morón	Spain	Morón de la Frontera	Parabolic trough	Completed in May 2012
50	La Africana	Spain	Posada	parabolic trough	Completed in July 2012
50	Olivenza 1	Spain	Olivenza	Parabolic trough	Completed in July 2012
50	Orellana	Spain	Orellana la Vieja	Parabolic trough	Completed in August 2012
50	Godawari Green Energy Limited	India	Nokh Village,Rajasthan	Parabolic trough	Started Production in June 2013
50	Enerstar Villena Power Plant	Spain	Villena	Parabolic trough	Completed in 2013
50	Megha Solar Plant	India	Anantapur	Parabolic trough	Completed in 2014
50	Delingha Solar Power Plant (Supcon)	China	Delingha	Solar power tower	Connected to grid on 30th December, 2018
31.4	Puerto Errado	Spain	Murcia	Fresnel reflector	Puerto Errado 1 completed in April 2009, Puerto Errado 2 completed in February 2012
22.5	Termosolar Borges	Spain	Borges Blanques	Parabolic trough biomass hybrid	Completed in December 2012
20	PS20 solar power tower	Spain	Seville	Solar power tower	Completed in April 2009
20	Kuraymat Plant	Egypt	Kuraymat	ISCC with parabolic trough	Production started June 2011
19.9	Gemasolar	Spain	Fuentes de Andalucía (Seville)	Solar power tower	Completed in May 2011
16.6	Brønderslev Smart Energy Concept with CSP ORC Biomass and heat pumps	Denmark	Brønderslev	Parabolic through	Started production on 30th December, 2016
11	PS10 solar power tower	Spain	Seville	Solar power tower	Commissioned in March 2011
5	Greenway CSP Mersin Solar Tower Plant	Turkey	Mersin	solar power tower	Commissioned in 2013
5	Kimberlina Solar Thermal Energy Plant	USA	Bakersfield, California	Fresnel reflector	Completed in 2008
5	Sierra SunTower	USA	Lancaster, California	Solar power tower	Commissioned in 2010

ORIGINAL RESEARCH ARTICLE

This study identifies the lack of policy directions as a key impediment to the uptake of solar thermal technologies in Nigeria, as is the case with the solar PV technologies. It is against this backdrop that the current study proposes possible policy initiatives and recommendations that will help achieve widespread adoption and application of solar thermal power technologies in the country. The policy directions and recommendations presented harmonize the necessary institutional aspects to evolve a comprehensive framework that will guarantee the adoption, viability, diffusion, and sustainability of solar thermal systems in Nigeria. The proposed framework can help eliminate the existing barriers impeding the widespread adoption of solar thermal technologies. Therefore, this study does not only provide insights into the recent developments of solar thermal-based electricity technologies but also presents a generalised policy framework that will be useful for understanding some of the prevailing issues of solar thermal technologies in developing countries.

Solar thermal technologies have some benefits that are attractive to energy planners and designers, decision-makers, governments and other relevant stakeholders. These benefits revolve around the techno-economic and environmental perspectives; one of them is clean energy production compared to the conventional fossil-based energy option [38–40]. Another benefit is that the technologies can be deployed in modular arrangements, thus, having a lower environmental impact compared to the existing grid-connected hydropower option, in terms of the issue of displacement of people [41]. Some of the technologies could be implemented in the deserts, thereby using land within communities for arable farming and other productive purposes. Though the solar thermal-based electricity technologies have a high initial capital cost, they have a competitive lifecycle cost being a renewable energy option [38,39]. Previous studies have also shown that solar thermal systems have the potential to produce cost-effective electricity [42–47]. The techno-economic modeling of the solar thermal power plant for local communities in Nigeria will be considered in the future work.

The remaining part of the paper is organised as follows: Section ''Background'' focuses on energy situation and barriers of solar thermal power adoption in Nigeria; Section ''A brief overview of solar power technologies'' presents an overview of solar thermal technologies with emphasis on the stand-alone systems (parabolic trough, central tower receiver, linear Fresnel and parabolic dish concentrators) and the hybrid systems (non-compact PV-CSP and compact PV-CSP); Section ''Policy frameworks and recommendations'' discusses the policy frameworks and recommendations; Section ''Future research'' presents the future research, while Section ''Conclusions'' concludes the paper.

Background

Energy situation in Nigeria

A World Bank report, in 2010, revealed that the per capita power consumption (kWh per capita) in Nigeria was 120.51 kWh [48]. Despite this figure, previous studies have shown that about 60% of Nigerians lack access to electricity and 80% of these people live in urban areas [49–51]. This figure is higher in rural areas because many rural communities in Nigeria are yet to be electrified. Most of these communities depend on fossil for cooking, lighting and heating. This difficulty to access electricity in Nigeria is due to the constant erratic supply in Nigeria. For example, Figure 1 [48] shows the capita electric power consumption (kWh per capita) in Nigeria between 2002–2010.

On paper, Nigeria has an installed capacity of approximately 7876 MW which can only cater for a sizeable amount of her population. However, as at 2010, the installed capacity fluctuates between 4000–4500 MW [49,52,53]. In recent time, Nigeria's average daily power generation is 2700 MW [52], this value is less than her forecasted peak load (8900 MW). As a result, the nation experiences consistent load shedding and blackout, especially in several quarters of the country. For example, the current electricity generation capacity of Nigeria is less than 5000 MW (As of April 2018); this value is far below the capacity believed to serve a population of about 180 million.

Power generation in Nigeria

Generation of power in Nigeria can be traced back to 1886 when two generating plants were installed to serve the then Colony of Lagos. Ever since then, the electricity corporation of Nigeria (ECN) has since changed to the National Electric Power Authority (NEPA) and was later renamed Power Holding Company of Nigeria (PHCN) after unbundling the electricity industry in 2005 due to the power sector reform process. The unbundling process paved way for the private company participation in the industry. The

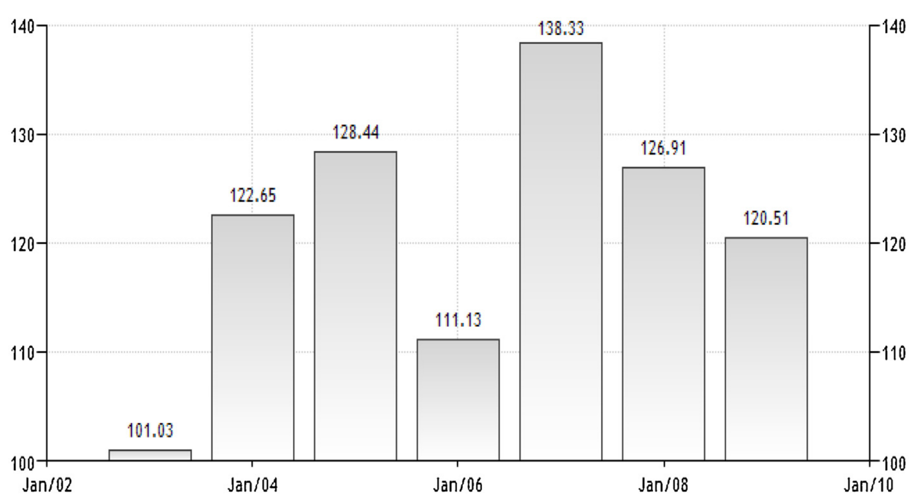

FIGURE 1

Per capital electric power consumption (kWh per capita) In Nigeria 2002–2010 [48].

process resulted in the creation of eleven distribution companies (DisCos), six generating companies (GenCos) and one government-owned transmission company. To properly manage the unbundling process, the Nigerian Electricity Regulatory Commission (NERC) was established. The commission serves as an independent regulatory body – licensing Independent Power Producers (IPPs) and regulating the operations of GenCos and DisCos.

The discretization of the DisCos area of jurisdiction (see Figure 2) has enhanced the objectives of the electricity reform ACT. For example, NERC has licensed several private Independent Power Producers (IPPs) to own and manage power projects. Furthermore, the Commission has developed a guideline for the bulk procurement of large capacity generation in form of embedded generation (including renewable energy) which will be directly fed into the distribution network. This provides local communities, state and local government, private utilities and other investors the platform to generate and sell or utilize power without going through the centralized transmission network. This policy further offers opportunities to DisCos to increase the power available for evacuation directly to consumers. With this, the transmission cost component of the tariff is eliminated. If the policy is properly implemented, it has been projected that about 40,000 MW generating capacity can be achieved by 2020.

Presently, there are more than 114 major grid sub-stations in Nigeria, and about 23 of these sub-stations are connected by 5000 km of 330 kV lines, while the other 91 are connected by 6000 km of 132 kV lines [52]. These sub-stations are made up of hundreds of kilometres of 33 kV and 11 kV lines [52]. And their performance is affected by poor power infrastructure. Most of the apparatus and equipment, such as the transmission lines and feeders, amongst others, are weak, due to poor maintenance culture and aging equipment. This problem is among the factors that are responsible for Nigeria's unreliable energy supply.

Renewable energy resources in Nigeria

Nigeria is blessed with huge renewable energy resources such as solar energy, wind energy, hydro and biomass [49,55,56]. These resources can be used to strengthen Nigeria's electricity mix. The estimated renewable energy resources in Nigeria is shown in Table 2 [57], while the FGN and IPPs electricity generation projections for 2013 to 2020 are presented in Table 3.

Hydropower

Nigeria's hydro-electricity source can produce about 11 GW, and this energy source is sufficient to meet the country's present electricity demand. This figure represents about 50% of cumulative installed grid-connected electricity generation capacity. Unfortunately, the hydropower currently generates only about

TABLE 2

Nigeria's renewable resources [57].

Energy sources	Capacity
Hydropower, large scale	10,000 MW
Hydropower, small scale	734 MW
Fuelwood	13,071,464 ha (forest land 1981)
Animal waste	61 million tones/yr
Crop residue	83 million tones/yr
Solar radiation	3.5–7.0 kWh/m^2-day
Wind	2–4 m/s (annual average)
Wave and tidal energy	150,000 T J/year

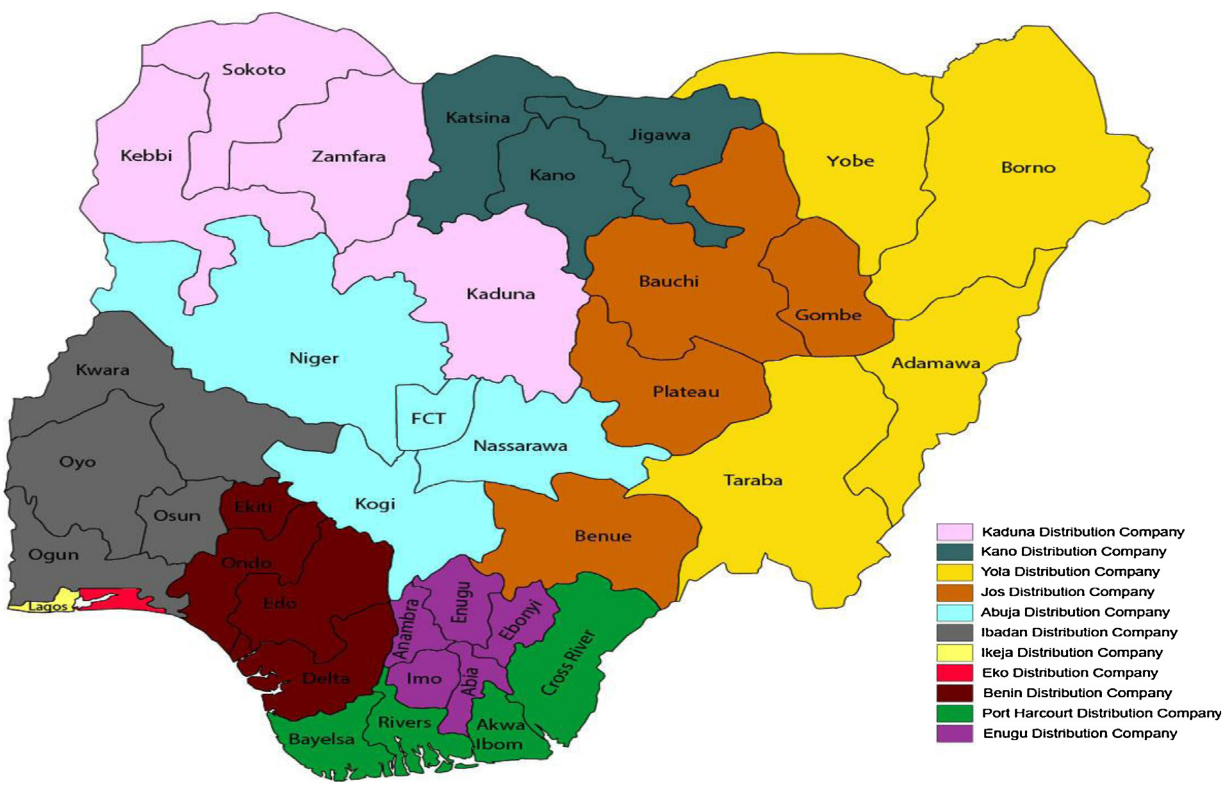

FIGURE 2

Coverage areas of the various DisCos [54].

10% of its estimated potential [49,52]. Available information showed water availability is not the major cause of this problem. For example, South-western and South-eastern regions of the country have higher annual rainfall with constant streams and rivers flow. These regions are, however, without any hydropower station; this is an indication that several hydro resources are yet to be exploited. While small hydropower may involve a reasonably high capital cost, it is not without its advantages. A low cost of operation and maintenance requirements and a long-life span have been identified as its main advantages. It is expected that with a very good feasibility report, any investment on hydropower project can be recouped before the useful life of the project. For example, the life span of a small hydro facility ranges from 20 to 30 years, as compared to 8–10 years for diesel engine generators.

Biomass

Nigeria has several biomass resources, such as grasses, wood, shrubs, animal waste, and other wastes from agriculture, as well as aquatic biomass, that can be found in different locations [49]. This energy resource is identical to fossil fuels because it is made up of hydrocarbons that are burnt to liberate heat. Current estimates show that about 61 million tonnes/year of animal waste can be accomplished and that about 83 million tonnes/year of crop residue can be produced. This implies that there is a huge possibility to harness the biomass resources for future electricity generation in the country. However, the past and present records of biomass input to power generation in Nigeria are unavailable.

TABLE 3

FGN and IPPs generation projections for 2013–2020 [58].

	Plant name	Capacity as at 2013 (MW)	Added capacity (MW)		
			2014	2015	2016
FGN GenCos	Zuregu				
	Afam IV & V	65	–	276	–
	Delta	360	–	200	–
	Egbin	1200	–	–	–
	Geregu	410	–	–	–
	Gurara		30	–	–
	Jebba	450	–	–	90
	Kaduna		200	–	–
	Kainji	220	–	220	–
	Mambilla		–	–	–
	Olorunsogo	180	–	–	–
	Omotosho	150	90	–	–
	Sapele Steam + gas	160	–	300	
	Shiroro	600	–	–	
IPPs	Alaoji	225	225	–	
	Calabar	112.5	450	–	
	Egbema	112.5	225	–	
	Gbarain	112.5	112.5	–	
	Geregu phase II	438	–	–	
	Ihovbor	450	–		
	Olorunsogo	450	225	–	
	Omoku	112.5	112.5	–	
	Omotosho phase II	450	–	–	
	Sapele	450	–	–	

FGN – Federal Government of Nigeria, IPPs – Independent Power Producers.

Solar energy

Nigeria's annual average solar radiation varies from about 12.6 MJ/ m^2-day (3.5 kW h/m^2-day) in the coastal latitudes to 25.2 MJ/ m^2-day (7.0 kW h/m^2-day) in the extreme Northern region of the country [51]. This gives an average annual solar energy intensity of 1934.5 kW h/m^2-year; thus, over a year, an average of 6,372,613 PJ/year (around 1770 thousand TWh/year) of solar energy falls on the whole land mass of Nigeria [49,57]. This is about 120 thousand times the total annual average electrical energy generated by the PHCN [49]. In order to properly plan for this kind of energy in Nigeria, decision-makers need to have a clear picture of Nigeria's solar radiation distribution as shown in Figure 3 [49].

For Nigeria to initiate key national initiatives on PV technologies for solar energy, robust research and capacity in form of funding is required. In recent times, PV technologies in Nigeria have shown a growing prospect in terms of efficiency and costs of procurement and installation [49]. This is because the lifespan of solar cells ranges from 25 to 30 years and this lifespan makes them to be remarkably attractive to investors [49]. As of today, investors usually import most of the PV cells. The National Agency for Science and Engineering Infrastructure (NASENI) Solar Energy Limited, in Abuja, Nigeria assembles solar cells into modules. The solar module plant began operation in 2011. Some of the applications of the solar PV system include the solar home systems, rural and residential water pumping, heating systems, refrigeration, and telecommunications.

However, one of the greatest challenges of solar PV-based technologies in Nigeria is the issue of system failure. This problem is making people lose confidence in the viability of PV technologies. In addition, solar PV systems analysis, especially the techno-economic evaluation aspect has been widely presented in the literature [61]. In order to strengthen the country's future energy mix, it is necessary to focus research in a new direction such as the solar thermal power technologies. This is because Nigeria has huge solar energy resources across its six geo-political zones.

Wind energy

Currently, there are few wind turbines in Nigeria. This is because Nigeria has relatively low wind speed regime. Nigeria experiences varying levels of wind speed; lower speed of about 1.4–3.0 m/s in the south and a moderate speed of about 4.0–5.12 m/s in the far north. The southern part of the country experiences relatively low wind speed with the exemption of the coastal regions and offshore regions having peak wind speeds occurring between April and August [49,55,56]. A previous study on wind energy technology revealed that total useful wind energy reserve at 10 m height in Nigeria varies between 8 MW h/year in Yola and 51 MWh/year in the mountain areas of Jos Plateau, while it is as high as 97 MW h/year in Sokoto [57].

Consequently, Nigeria is a low/moderate wind energy region, and this practically makes wind energy application in the country virtually minimal. The issue of lack of technical expertise also hampers the technology growth in the country. Despite these issues, wind turbines have been used in some areas to generate electricity. For example, there is a wind electricity project in Sayya Gidan Gada at Sokoto [49,56].

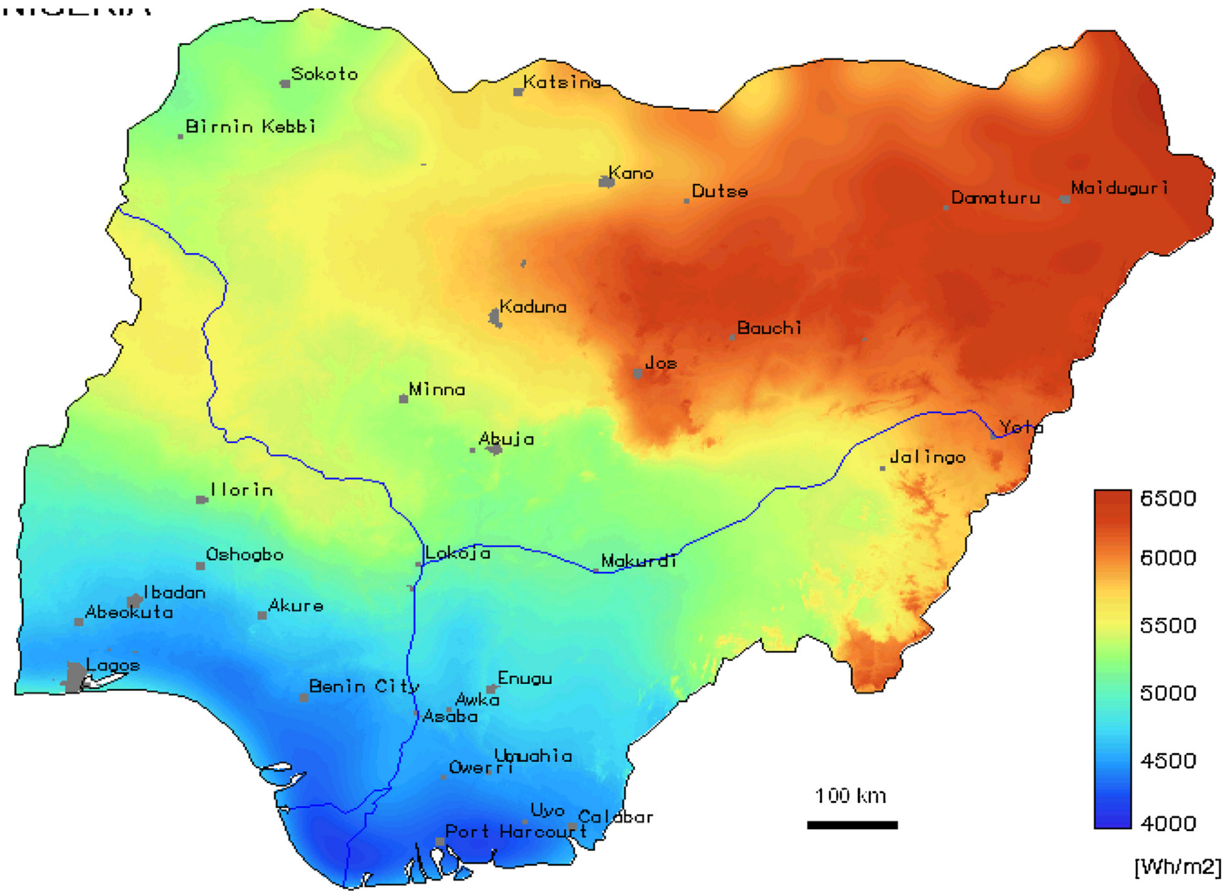

FIGURE 3

Solar radiation map for Nigeria [49].

Barriers to the adoption of solar thermal solutions in Nigeria

The role of the government in institutionalizing sound policies and initiatives cannot be overlooked when advocating for the adoption of solar thermal technologies utilization. For example, they are to provide an enabling environment that would encourage the influx of investors with the guarantee of recouping investments within a reasonable time frame. This will enable investors to recoup the huge initial costs involved in solar thermal technologies. Furthermore, considering the importance of solar thermal technology for off-grid application such as water pumping, drying of foodstuff, grinding, etc. and the high energy-poverty rate among these rural homes, there is a need for government intervention in ensuring access for the rural communities. In South Africa, for example, the Free Basic Electricity (FBE) programme ensures that poor off-grid homes get solar home systems (SHS) with connection and installation costs fully subsidized by the government. Furthermore, 80% of monthly fees are subsidized by the government ensuring that the energy service companies (ESCO) and concessionaires recouped their investments [89].

Another country which has a very good renewable energy policy is Kenya. It has adopted a tax route by exempting all imported light emitting diode (LED) lighting equipment and solar components from import duties. This has greatly encouraged the local assembly of solar products and solar pico-powered lighting system (PLS) [58]. Ethiopia is another country with a very good renewable energy policy. It has implemented a 45% subsidy on all solar equipment as part of its energy for rural transformation (ERT) program and this has encouraged suppliers of solar equipment to invest in its rural areas. Additionally, in an attempt to reduce the purchase cost of PLS equipment, they have also developed a policy that provides for the exemption of solar equipment from inland duties and surtaxes [58].

A critical observation of the cases mentioned has shown that consistency in government policy and the implementation of recommendations, especially tax waivers and subsidies, are the bedrock for successful renewable energy policy implementation. The current study briefly highlights some prominent factors that have impeded the adoption of solar thermal technologies in Nigeria.

Lack of understanding of solar thermal technology and its potential

In Nigeria, a major barrier to the adoption of solar thermal technology has been a lack of understanding of the technology, its potential and costs. For instance, the short, medium and long-term projections for solar thermal was 0 MW, 1 MW, and 5 MW, respectively, when compared to 5 MW, 120 MW and 500 MW for solar photovoltaic [90]. The position of National Energy Policy further corroborated this observation [91] and also posited that apart from traditional open-air drying, solar energy technologies are not optimally utilized in Nigeria. With the current technological advancements in solar thermal energy technologies in terms of implementation, operation and maintenance, these technologies application is expected to increase in Nigeria. For example, solar thermal (concentrating solar power, CSP) averages 12–18 cent/kWh for power generation and 2–25 cent/kWh for solar hot water/heating purposes compared to 20–40 cent/kWh for rooftop solar photovoltaic systems [92].

Policy inconsistency and agency conflicts

A major observation of the energy sector in Nigeria presents a peculiar case. In regulating the energy sector, there has been the National Electric Power Policy (NEPP) of 2001, which was a precursor to the Electric Power Sector Reform (EPSR) Act of 2005. Aside the EPSR Act of 2005, there have been numerous policies such as National Energy Policy (NEP), Rural Electrification Policy (REP), National Energy Master Plan (NEMP), Renewable Energy Master Plan (REMP), Renewable Electricity Policy Guidelines (REPG), Rural Electrification Strategy and Implementation Plan (RESIP), National Renewable Energy and Energy Efficiency Policy (NREEEP) etc. between 2001 and 2016.

In addition, a major disadvantage of NEPP has been conflicts about the government's stance on solar thermal and other renewable energy technologies. For example, the short, medium and long-projection for solar thermal was 0 MW, 1 MW and 5 MW, respectively, while 300 MW, 2136 MW and 18127 MW were projected for solar thermal (electricity). However, the other thermal operations (water heating, cookers, dryers, stills and pasteurizers), 6550, 119,000 and 318,000 units (cumulative) were to be delivered for the short, medium and long-term [93].

This inconsistency, which is mostly occasioned by a change in leadership, creates implementation issues owing to major variations between the new policy and the existing policy. Furthermore, in coordinating the operations of the power sector, different agencies, such as Energy Commission of Nigeria (ECN), Nigerian Electricity Regulatory Commission (NERC) and the Rural Electrification Agency (REA), play active roles in this policy implementation.

Among these agencies, ECN is the apex government organ for the formulation of the most appropriate energy planning and monitoring energy frameworks as well as evaluating the energy policy and implementation. This commission sometimes involved in executing projects that fall within the scope of the REA. REA has been tasked with achieving 60% rural electrification by 2020. It intends to achieve this task by connecting about 1.1 million rural households to electricity supply annually.

Lack of enabling laws and targets for solar thermal capacity expansion

In Nigeria, policy somersaults are a frequent occurrence owing to the duplicity of conflicting policies on renewable energy technologies. For example, The EPSR Act of 2005 [94] which gives legal backing to the establishment of NERC and REA is silent on specifics about targets for the REA and ECN, in the diversification of Nigeria's energy mix. This problem sometimes discourages investors to invest in renewable energy projects. Some investors have cited the lack of enabling laws that make certain renewable energy targets to be met and thereby hinder expansion of renewable energy projects. With this situation, investors have little faith in the assurances offered by the government, since there is no legal backing for the abounding policies.

Non-implementation of EPSR Act on rural electrification fund

The EPSR Act of 2005 [94] makes provision for a rural electrification fund (REF). In the ACT, REF is "to promote, support and provide rural electrification programmes through private and public-sector participation." However, while the act vaguely specifies the "contribution rates and payments" to the fund including fines, there has been no consistency in prosecuting defaulters. It may be argued that the inability of the government to meet its counterpart funding may have emboldened relevant companies and agencies to default repeatedly and brazenly in funding the REF.

Lack of incentives for renewable energy technologies

Incentives (financial and fiscal) have been recognized as paramount to promoting renewable energy and energy efficiency projects in Nigeria [93]. Financial incentives refer to subsidies and grants that are usually targeted at the demand side – FBE in South Africa while fiscal incentives target the supply – tax breaks and duty waivers etc. Unfortunately, the absence of robust legal backing to incentive proposals in Nigeria has impeded the smooth take-off of solar thermal projects in Nigeria [93]. For instance, the serial default of government to counterpart funding of projects from joint ventures in the oil and gas sector to other projects shows government weakness to honour agreements; government is not deemed "credit-worthy" to guarantee private investments. Another obstacle to this take-off is that financial institutions are wary of investing in renewable energy projects owing to the "non-bankability" of such projects.

Lack of technical expertise

Currently, technical skill shortage is one of the major problems facing Nigeria [58]. Low skills shortage might translate to huge costs of solar thermal plant maintenance, and this problem might lead to this plant being abandoned. This skill shortage is caused by the failure of vocational training institutes to develop local capacity in solar thermal applications with optimum results and in some cases, utility companies in Nigeria are forced to invite experts from other countries. The cost of sustaining foreign skilled workers could become prohibitive, and this cost can also impede solar thermal adoption. While skill transfer can be used to manage this problem, there is a need for agreements with foreign solar thermal companies in future partnerships to have clauses that make for the transfer of the technologies to Nigerians who in turn can localise future training of experts.

High technology cost and lack of funding

Generally, renewable energy technologies are associated with a high cost of implementation, of which the solar thermal power system is not an exemption. This challenge and lack of fund, are part of the barriers to the uptake of solar thermal systems in Nigeria. Because of these problems, most communities are comfortable with the use of petrol or diesel generators to meet their daily energy needs because of its relatively low capital cost.

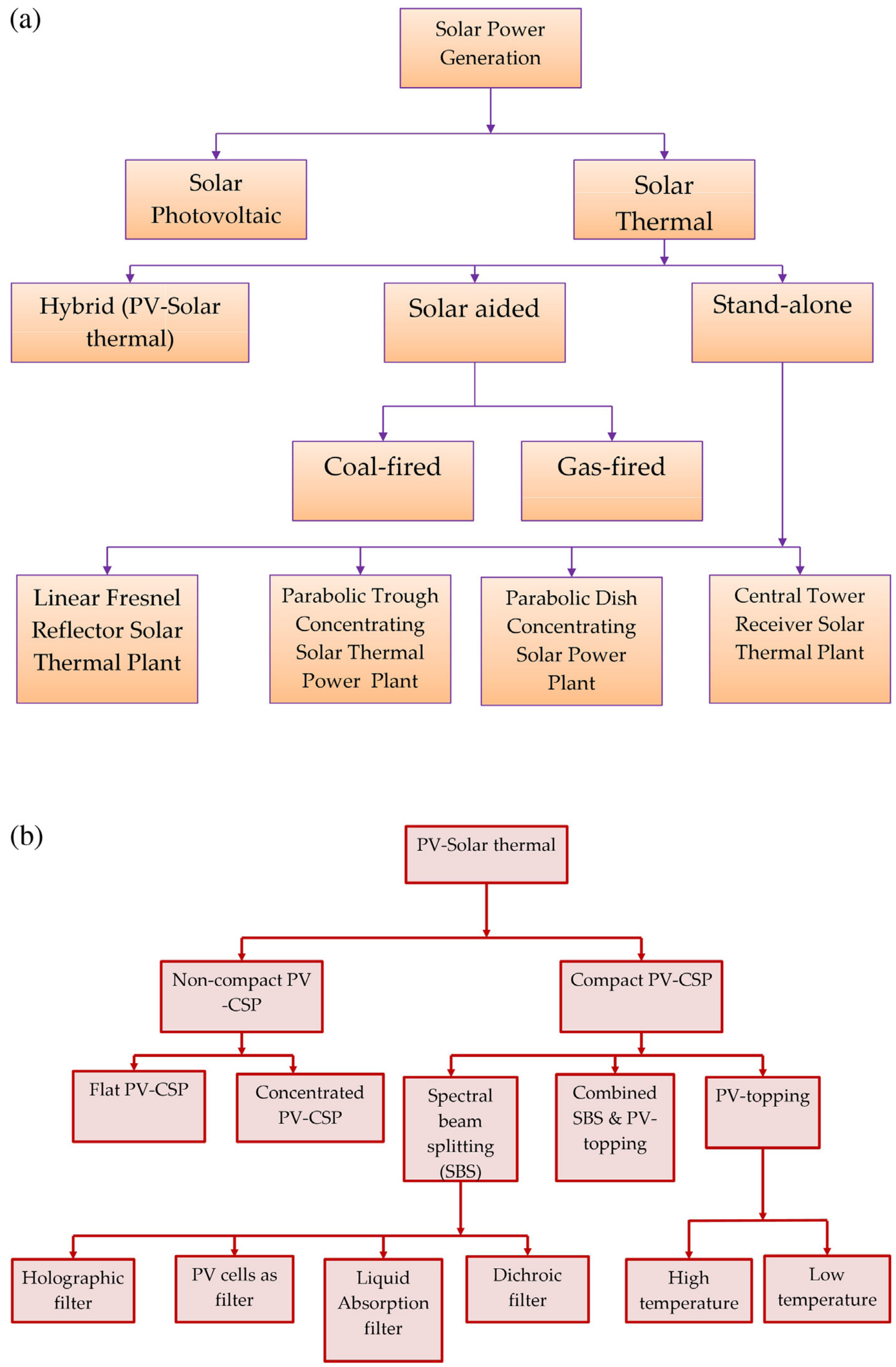

FIGURE 4

(a) Schematic view of solar power generation methods [16]. (b) Classification of the PV-CSP hybrid system [63].

A brief overview of solar power technologies

The role of energy in the development of any nation's economy is very essential due to its relationship with the national gross domestic product (GDP) [59]. The energy industry is the driving force and backbone of any economic growth since its output serves as input into goods and services. According to Ref. [59], "the energy sector penetrates its reach deep into various economies as an investor, employer and purchaser of goods and services".

To quench the thirst for the increasing appetite for energy, various sources of conventional energy have been employed. This has improved the quality of life, but with consequences. The most prominent of these challenges is the negative environmental impact of the fossil powered plants. This has led to global warming and climate change [60]. Furthermore, fossil fuel sources are fast depleting, and therefore, bring about the critical issue of energy generation sustainability. Hence, there is a need to extend research into sustainable resources and technology in order to meet future energy demands. Adoption of renewable energy will answer the question of both resource and environmental sustainability to a large extent.

Apart from fossil fuels, nuclear and large hydropower, some other renewable energy sources are becoming widely acknowledged means of meeting the current global energy demand and supply scenarios. Some of these sources include wind energy, micro-hydro, solar photovoltaic, biomass, tidal, geothermal energy and solar thermal power plants. Out of all these energy sources, solar power generation has been identified as the most versatile and viable option that can adequately generate electricity for future needs [61]. The solar power generation has various methods it can use to generate electricity, as shown in Figure 4 (a) [16]. The solar thermal systems have some promising benefits because of their diverse technologies.

Solar thermal-powered systems

Solar thermal electricity is obtained from the direct collection and conversion of solar energy. It harnesses the energy from the sun to generate electricity through a thermodynamic process. The general approach to energy conversion using solar thermal energy is presented in Figure 5. The conversion process for electricity generation is initiated when solar energy is collected and converted to heat by the receiver/collector system. The converted energy is transmitted by a heat transfer fluid to the storage and then to a boiler, where steam is produced [3]. The steam supplied is used to turn the blade of the turbine in the heat engine, and this is converted to mechanical energy that spins the prime mover of the generator. The heat and electricity can be obtained at the output stage, depending on the design. At each conversion stage, energy losses are expected.

Apart from energy loss, another challenge with solar thermal power generation is that with increasing temperature, the efficiency of the solar collector decreases, while the efficiency of the heat engine increases [62]. Hence, it is the desire of designers and researchers to select optimal operating conditions for a solar thermal plant. Their efforts have yielded different solar thermal power technologies such as the stand-alone systems (parabolic trough concentrator (PTC), central tower receiver concentrator (CTRC), linear Fresnel reflecting concentrator (LFRC) and parabolic dish concentrator (PDC)); hybrid systems (non-compact PV-CSP) and compact PV-CSP) and the solar-aided systems (coal-fired thermal plant and gas-fired combined cycle power plant), shown in Figure 4(a) and (b) [63,64].

Stand-alone systems

Parabolic trough concentrator

Parabolic trough concentrator has been identified as the most commonly used solar thermal plants of the medium temperature range. This plant is economical in terms of cost and it is also the most developed plant for commercial purpose. The PTC has the tendency to deliver output fluid temperature of about 500 °C. This kind of solar thermal technology is also known as the line-focusing parabolic collector. Its configuration is made up of long parallel assembly of reflectors created by shaping plates of reflective materials into a parabolic form. In this configuration, the receiver (absorber tube) is placed at the focal point of the reflector or concentrator, as shown in Figure 6. The curved parabolic reflective material reflects the sunlight onto an absorber tube positioned at the focal point of the parabola. The absorber tube is filled with fluid that captures the heat and transfers it to the boiler or other devices to produce steam. The receiver is usually a black treated metal tube covered with a glass tube. It has a space between the pipe and the glass cover to reduce heat losses through convention. The parallel assembly of the parabolic mirrors is either in a north-south or an east-west axis orientation. Each orientation has its own merits and demerits based on the location and the output of the system. The

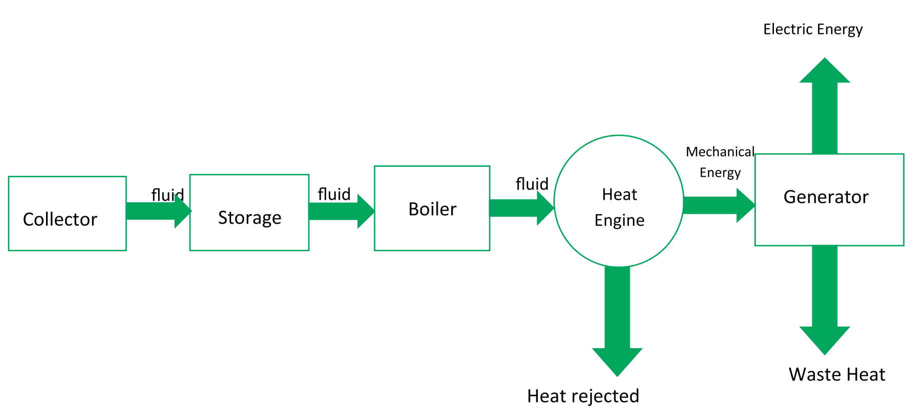

FIGURE 5

Schematic diagram of solar thermal power [100].

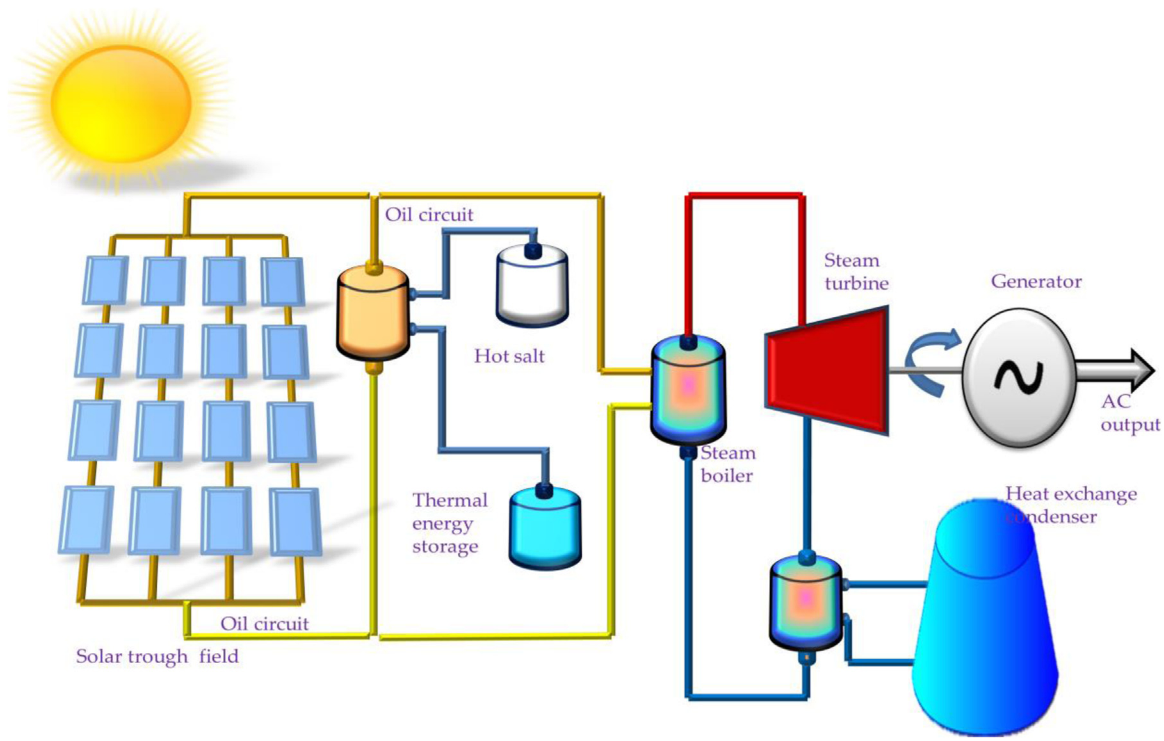

FIGURE 6
Parabolic trough concentrator (PTC) [67].

rows of parabolic mirrors are fitted with tracking devices, which constantly keep track of the sunlight for optimal collection of solar radiation. During the night hours, the parabolic trough concentrator will return to its original position.

Several studies have been reported on the PTC in the literature, but a few of them is mentioned in this study that also provides relevant background on the solar thermal power aspect. One of these studies deals with the design of a tracking mechanism of a PTC system based on mathematical algorithms that estimate the sun position [66]. Typically, a PTC has the capacity to collect an average of 65% of the incident solar irradiance. Hence, the net generation to incident solar radiation ratio (peak conversion efficiency) of a PTC ranges from 0.20 to 0.25% (see Figure 6 for more information on a PTC design) [67]. A study has also examined the prospect and performance of single-axis tracking parabolic trough solar collectors using typical meteorological year input data for 11 different sites [68].

A study was carried out on the viability and environmental impact assessment of the electricity generated by a 17 MW solar thermal plant. The work considered a central tower technology and a 50 MW solar thermal parabolic trough technology in Spain [69,70], identifying the prospects of improving the plant to reduce negative environmental impacts.

Central tower receiver concentrator

The central tower receiver concentrator (CTRC) technology concentrates light to a remote central receiver that is located on a tower, unlike the PTC that reflects light onto a focal line. As illustrated in Figure 2 [54], the configuration of a CTRC comprises of a central tower and it is surrounded by a large array of sun-tracking flat mirrors (heliostats). The mirrors track and focus the incident sunlight onto a receiver. The receiver is located at the top of a tall tower where concentrated sun rays heat up a fluid up to about 1050 °F. The hot fluid can either be instantly used to generate electricity or stored.

Typically, the reflective surface area of each heliostat installed on a common pillar ranges from 50 to 150 m^2. To achieve the same efficiency as the parabolic concentrators, there is a need to increase the size of the heliostat field. This, however, brings into limelight land use policies, higher environmental impact as well as increased investment capital. Therefore, CTRC systems are best suited for deserts and arid regions with higher irradiance and where the value of land with respect to other application is quite low. In the CTRC technology, the total efficiency from solar radiation to electricity is about 17% [71].

Several works have also been directed towards CTRC solar thermal plants, for example, a model for a large area solar concentrator for central receiver power plant has been reported [72]. The model considered steering constraints on mirror angles and shadow effects by blocking the incident or reflected sunlight. Another work is reported in Ref. [73] that considered the design and construction of a secondary concentrator to enhance the performance of hybrid power plants. A study has also presented a technical and economic analysis of various solar-hybrid gas turbine cycles with low and medium capacity. The work in Ref. [74] proposed six different heliostat configurations for CTRC. It also discussed how to get maximum efficiency in a typical solar thermal central receiver system.

Presently, there are two commercial-scale CTRC projects that are operational in the U.S. The Ivanpah Solar Electric Generating System (392 MWe) and the Crescent Dunes Solar Thermal Plant (110 MW) located in southwestern Nevada, as shown in Table 1. Apart from the U.S., Spain also has several power tower systems.

Linear Fresnel reflecting concentrator

Generally, the linear Fresnel reflecting solar concentrator (LFRSC) is made up of long narrow flat mirror components that are attached to a horizontal base [75]. These components are arranged and skewed at an angle which allows all incident sunlight rays that fall on them to be reflected on a common focus. Small parabolic or trapezoidal mirror are occasionally fixed on top of the receiver to enhance the focus of the sunlight. The absorber (which is usually a tube or series of a tube containing heat transfer fluid) is placed on the focus of the arrangement and is used to absorb the concentrated radiation. Hence, the absorber is a major component in the absorption of solar energy. During operation, it is heated up due to the incident sun rays that fall on it [76,77] and then emits wavelength radiation which leads to heat loss from the surface of the absorber. Consequently, the heat loss leads to the reduced thermal efficiency of the collector. Conduction and convention are other sources of heat loss [76–78]. It is worthy of note that absorbers with selective surface coatings exhibit high solar radiation absorption rate and low emissivity for thermal radiation loss [79–81]. Hence, the application of selective surface coatings on absorber reduces radiation loss [82–84].

Parabolic dish concentrator

The parabolic dish concentrator uses parabolic dish-shaped mirrors to focus sunlight onto a receiver placed at the focal point of the dish, as shown in Figure 7 [86]. The sun provides the heat energy for heating the fluid in the receiver to a temperature as high as 750 °C. This fluid, in turn, serves to generate electricity in a small Stirling Engine, or Brayton cycle engine connected to the receiver. Parabolic dish systems are approximately 25% efficient and are described as the most efficient of all the solar thermal technologies which are about 20% efficient. From Figure 7, the principal components of the parabolic dish solar concentrator include base support, concave dish frame, reflecting mirrors, a conversion unit, and sun-tracking system. To harvest optimal solar energy, the parabolic solar concentrator dish uninterruptedly tracks the sun throughout the day using a dual axis tracker with slew drivers. From Figure 7, the first slew driver guarantees the rotation of the dish about the vertical axis for all possible azimuth angles, while the second slew driver ensures rotation of the dish about the horizontal axis through all possible elevation angles. This concentrator has also received considerable research attention. One of such research focuses on the design, development and performance characteristics of an economical solar steam generating system based on parabolic dish technology [85].

The solar thermal power system can typically be sectionalized into two major parts: the collector-receiver and heat engine subsystem [87,88]. A collector consists of a number of reflective surfaces (e.g. mirrors) that are arranged in segments to track and collect the sunlight. The system's heat engine consists of a heater or a boiler heat exchanger, a turbine, a condenser, a pump and regenerator, as shown in Figure 8 [88]. As indicated in Figure 8, an absorber tube per collector is used to absorb the solar energy. A thermal fluid is circulated to receive the heat energy collected by the absorber tubes. The energy from the heated thermal fluid is then transferred to the heat engine through a boiler heat exchanger. The heat engine circuit (in this case, a Rankine cycle) consists of a boiler heat exchanger, a turbine, a pump and a regenerator [88].

Hybrid systems

Non-compact PV-CSP

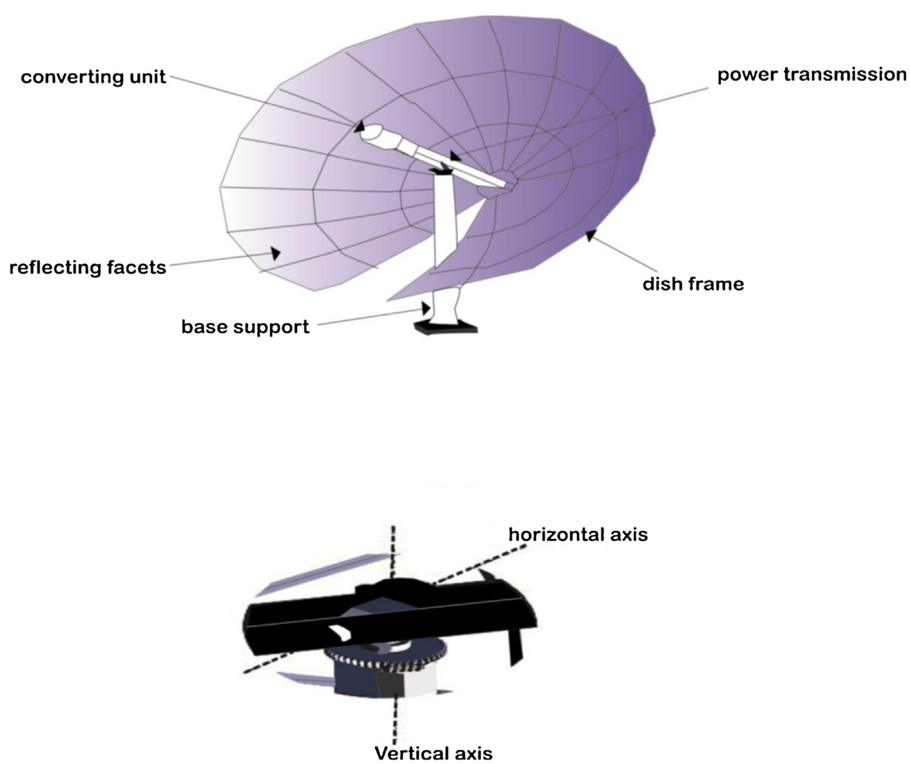

FIGURE 7

Schematic diagram of a dish frame connected to the base, and the transmission system [86].

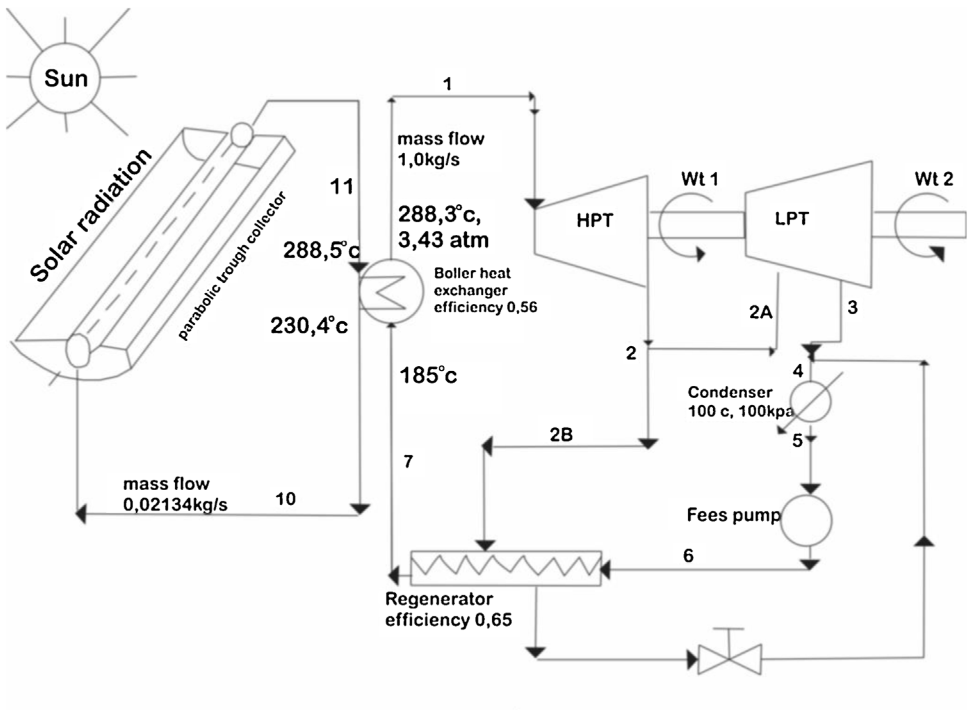

FIGURE 8

Sketch of a solar power system [88].

The configuration of this system is such that the solar PV and the CSP parts can operate independently [63]. The system is configured by the ''power dispatching'' or the ''control'' mechanism that provides high-quality electricity for the on-grid and grid-independent applications. The PV system is designed to provide a part of the required power for the CSP system, thus, the energy cost of the CSP technology can be reduced with the integration of the solar PV system. One of the features of this system is that the solar PV and the CSP systems are matured technologies, and there are a few technical issues with their combination. The flat PV-CSP and the CPV-CSP are the main types of the non-compact PV-CSP as shown in Figure 4(b).

In the case of flat PV-CSP technology, the CSP system with a cavity receiver, solar PV cells, and the associated auxiliary system may be positioned in the south/north area that is not covered by the heliostats to generate energy for the power grid and the CSP ''subsystem'' [64]. Heat exchangers could also be integrated with the hybrid arrangement, while the cooling water of the PV subsystem may be used to achieve the pre-heating of the working fluid of the CSP subsystem. This way, the thermal economy of the hybrid arrangement could be improved. The CPV cells or modules could also be used in the non-compact PV-CSP hybrid technologies.

Compact PV-CSP

Apart from the non-compact PV-CSP hybrid technology, the solar PV and the CSP systems could also be combined more ''compactly'' considering their different energy conversion properties [63]. Technically, the photons with energy below the bandgap of the PV cells are transmitted, and they generate heat in the solar substrates. However, the photons with energy above the bandgap of the PV are partly converted to electric current by this process, and the other portion is dissipated as heat by a process called thermalization. As a result, the incident light on the solar photovoltaic cells or modules can partly be converted to electric current, leaving no room to combine with other systems to improve the overall energy conversion efficiency.

The compact PV-CSP hybrid technology is designed to overcome the identified shortcoming by making full utilization of the solar energy, similar to the other solar hybrid systems such as solar/biomass, and solar/thermo-electric systems [63]. The basic compact PV-CSP technology includes the PV-topping, spectral beam splitting and the combined SBS and PV-topping, as shown in Figure 4(b).

In the case of PV-topping method, the dissipated heat energy from the solar PV cells is recovered to produce electric power through the CSP system [63]. This system involves the use of the solar cells as the heat receiver and the PV converter. In addition, solar radiation is usually concentrated in order to reduce the cost of solar cells integrated and achieve a very high thermal energy. The PV-topping method has low and high-temperature configurations. However, the SBS configuration presents another promising method of the PV-CSP hybridization. When adopting this technology, the energy conversion efficiency of silicon solar cells could exceed 0.4–0.5, which is higher than the value that can be achieved by solar cells under the full-spectrum radiation [65]. In this case, the working fluid temperature of the CSP system will not be limited by the solar PV cells, as the radiation below the bandgap will be re-directed to the thermal receiver of the CSP. The SBS may be classified according to its associated spectral beam filters such as the holographic filter, PV cells as filters, liquid absorption filter and the dichroic filter, as shown in Figure 4(b).

Policy frameworks and recommendations

In extending discussions on policy recommendations to the uptake and widespread utilization of solar thermal technologies in Nigeria, this study considers the barriers earlier mentioned in discussing the new policy directions before providing a framework that seeks to address the identified problems. The following are the possible ways to address the policy issues.

■ A comprehensive appraisal of solar thermal technology and its potentials

The varying stance taken by various policy drafts of government agencies in Nigeria on solar thermal technology and its projected growth expansion for short, medium and long-term projections shows the need for a comprehensive evaluation of the potential of this technology for power generation and heating purposes across Nigeria. This is necessary for planning and expansion purposes and for consistency in the government's position on technology utilization. In order to evaluate solar thermal potential across Nigeria, there is also the need to consider the spatial distribution of solar thermal potential. This is important as it enables the government to ensure equity and justice [95] during the conceptualization and formulation of policies for rural electrification (procedural justice) that will adopt this technology. A further implication of this is that the distribution of this technology across Nigeria should be done in an equitable way to adequately compensate for the stochasticity of solar irradiance across Nigeria – distributive justice. Additionally, in ensuring that cities are sustainable and conducive for habitation [96], it is important that deployed technologies do not adversely affect the natural bio-diversity of its site but safely interact [97]. It is, therefore, important to have pre-assessment (environmental impact assessments, EIAs) done on the potential impact of various solar thermal technologies on the ecosystem of a selected location for this technology deployment. This is to help to provide relevant information on the best solar thermal technology or combination of solar thermal technologies for a specific site.

■ Harmonization of government policies on solar thermal and its capacity expansion

A major barrier to the growth of solar thermal utilization in Nigeria has been policy inconsistencies due to changing government. There is, therefore, a need for a comprehensive policy roadmap on solar thermal (and other renewable energy) technologies for a specific time frame and backed up by law. This makes it binding on all government regime during the policy lifetime. And this will make successive government regime to build on the progress of the past government. Furthermore, a consistent and binding policy framework will ensure that there is a standard to which performance (in terms of milestones) could be benchmarked (measured). In addition, there must be a clear delineation of the responsibilities of the ECN, REA and other related ministries, departments and agencies (MDAs) involved in renewable energy policy making and implementation. This is to prevent overlapping of duties and improve their efficiency.

■ Establishment of vocational training institutes for local capacity development

The significant growth witnessed in the oil and gas sector, especially the significant increase in indigenous oil servicing companies, has been linked to the local content Act [98] which mandated a certain percentage of local sector participation in all associated oil and gas exploration. This Act has led to the development of a critical crop of local experts. Furthermore, the establishment of world-class oil and gas training facilities in Nigeria has facilitated the continuous training of new crop of semi-skilled experts in fabrication, especially for water welding. Similarly, there is the need for government to have a vocational training institute on solar thermal technologies with enabling laws that mandate foreign investors and technology companies to recruit specifically from these institutes. In addition, the government should ensure the regulation of solar thermal technicians by ensuring that only certified technicians (by the Nigeria Society of Engineers, NSE) can be recruited.

■ Sustainable financing and incentive

A major impediment to the adoption of solar thermal energy technologies has been lack of financial support (e.g. grants, subsidies, loans, research funding etc.) for private and foreign investors. This is as a result of the poor framework that will ensure the recoup of investments. Thus, most solar thermal and other renewable energy projects end up being unsustainable as they are unable to generate funds for basic operations and maintenance activities. While it is agreed that government has a duty to ensure that it provides its citizens with adequate electricity, it does not obviate the need for homeowners to demonstrate social responsibility by ensuring they fulfill their counterpart funding (which are usually computed with respect to their earnings and poverty level). This way, the government can guarantee funds for basic operations and maintenance expenses. Furthermore, there must be fiscal responsibility on the part of the government in ensuring that it meets its funding requirements timeously.

A non-contact cash transfer scheme must be ensured in the financing chain, but instruments and certificates of satisfactory performance are needed to reduce (or possibly eliminate) corruption cases. Lastly, the laws governing the funding and management of the rural electrification fund must be dutifully followed if the targets set must be met. The recent Industrial Development (Income Tax Relief) Act [99] which provides a list of pioneer industries that are to be exempted from tax for an initial period of 3 years is a welcome development. However, considering the huge costs involved in the initial set up of solar thermal plants, there is the need for government to go beyond tax incentives by including duty waivers for renewable energy technology products that cannot be locally sourced. This is to speed up solar thermal plants development in Nigeria and reduce the cost of extending solar thermal power to homes. However, the extension of tax breaks and waivers to solar thermal energy technology companies must be complemented by firm investments in training institutes and development of local capacity in solar thermal technologies.

■ Private partnerships

The role of the private sector in boosting solar thermal and other renewable energy technologies in Nigeria cannot be over-emphasized. The privatization in the telecommunications sector which led to the active participation of the private sector contributed to its rapid development. Similarly, the successes of the Bonny Utility Company (BUC), Okpai power plant by Nigerian Agip Oil Company (NAOC) with installed capacity (as at March 2012) of 480 MW and the Afam VI power plant by SPDC with installed capacity (as at March 2012) of 650 MW are largely due to the involvement of the private sector [58]. The government must, therefore, seek for ways to leverage on the massive support structure of the private sector in boosting solar thermal and other renewable energy technologies through public-private

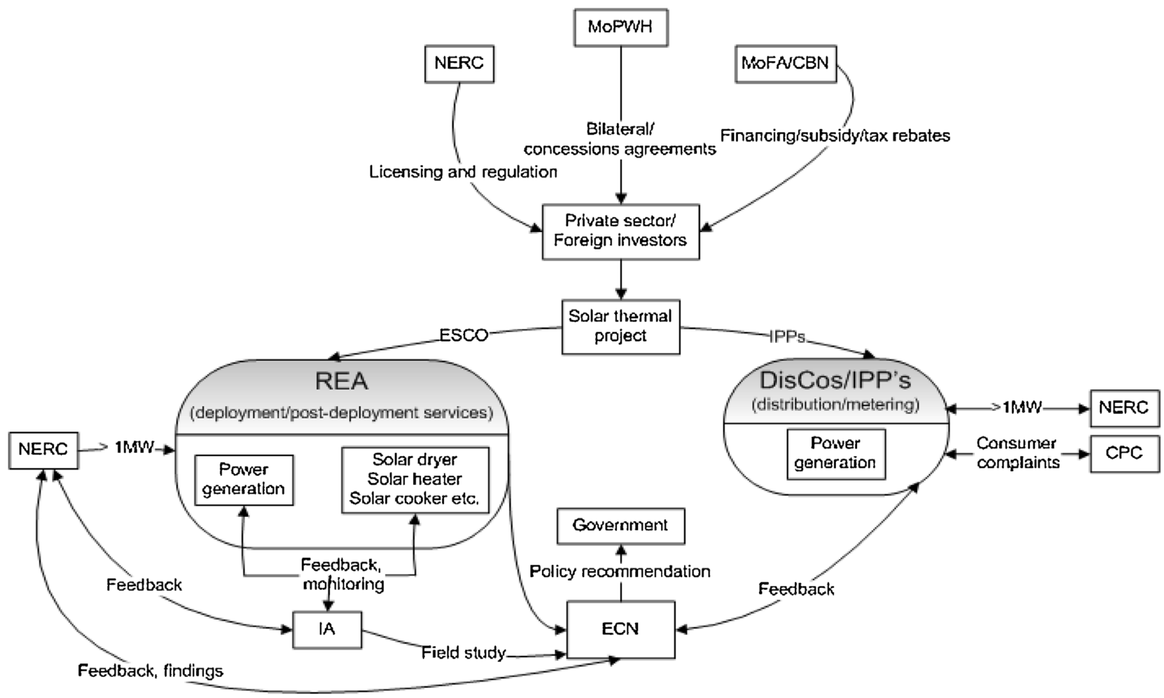

FIGURE 9

The proposed sustainable framework for the deployment of solar thermal projects in Nigeria.

partnerships (PPPs): concession agreements. In advocating for a more pragmatic approach to the adoption of solar home systems, [58] proposed a sustainable roll-out scheme that involved the active participation of all necessary players. In adopting the model set out in Ref. [58], Figure 9 highlights the various players and their roles in executing solar thermal projects (STPs). It is observed from Figure 9 that bilateral and concession agreements are handled by the Ministry of Power, Works and Housing (MoPWH) on behalf of the government. Thereafter NERC licenses the investor companies to operate as Independent Power Producers (IPPs).

The financing structure, such as tax reliefs, duty waivers and among others, are coordinated by the Ministry of Finance (MoFA). The execution of the solar thermal project could either be off-grid for rural communities, in which case REA supervises the activities of the ESCO [in rural communities, or in urban communities (in which case the IPPs work in synergy with the DisCos)]. For urban deployment, the consumer protection council (CPC) and NERC handle cases of consumer complaints, while NERC and REA handle complaints from rural areas. Independent assessors (IA) continuously monitor the operations of ESCO at the rural level to ensure complaints of consumers are dealt with satisfactorily, while ECN makes a policy recommendation to the government based on field study and feedback from REA, NERC, DisCos/IPPs, and IA. An important observation from Figure 9 is the prevalence of feedback, which is important in allowing regulatory agencies as well as private investors to align their investments with customer expectations.

Future research

This study has presented a brief overview of solar thermal, and it focused on the existing solar thermal power technologies for electricity generation. It also examined the policy directions for these technologies adoption and application. While this study has further the frontier of these technologies' adoption and application, there is a need for a future research study that will consider the technologies' modeling and analysis for remote communities. The focus of such a study is to consider the techno-economic feasibility of a solar thermal power plant and then compare it with a typical solar PV power generation plant.

Conclusions

This study has presented a brief overview of solar thermal power generation technologies, and it focused on the different kinds of technologies and their applications. The technologies discussed include the parabolic trough, central tower receiver, linear Fresnel reflecting and parabolic dish concentrators. Based on the study's findings, several barriers affect the adoption and development of solar thermal technologies in Nigeria.

Some of these barriers are lack of understanding of solar thermal technology, policy inconsistency and agency conflicts, lack of enabling laws and targets for solar thermal capacity expansion. Other identified barriers are non-implementation of EPSR Act on rural electrification fund, lack of incentives for renewable energy technologies, lack of technical expertise, high technology cost and lack of funding, and the previous experience of solar PV systems failure that makes people lose confidence in renewable energy systems in the country. Among these barriers, lack of enabling policy is the key factor that impedes solar thermal power technologies adoption, application and diffusion in Nigeria.

Some of the recommended solutions to the identified barriers include a comprehensive appraisal of the technology and special distribution assessment for the technology, environmental impact assessment. Other solutions are harmonization of government's existing energy policies to include solar thermal in the energy mix, building local capacity and competence, sustainable financing, incentives and involvement of the private sector. Based on these recommendations, this study, therefore, developed a policy framework that addresses the identified barriers to solar thermal power technologies adoption, application, and diffusion. The framework will provide useful insights into the major issues that affect community-based or regional solar thermal power systems in developing countries around the world.

The significance of this study is that it provides useful insights into the solar thermal systems development and application, and a better understanding of the major issues affecting the uptake and development of community-based or regional solar thermal power systems in developing countries around the world.

The authors declare that there is no conflict of interest on the paper entitled ''Possibility of solar thermal technologies in Nigeria: Challenges and policy directions''.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgements

This work was carried out with the aid of a grant from the International Development Research Centre, Ottawa, Canada, www.idrc.ca, and with financial support from the Government of Canada, provided through Global Affairs Canada (GAC), www.international.gc.ca under the framework of the Mathematical Sciences for Climate Change Resilence (MS4CR) program administered by AIMS-NEI, www.nexteinstein.org.

References

[1] Renewables 2018 Global Status Report. Renewable Energy Policy Network for the 21st Century (REN21). http://www.ren21.net/status-of-renewables/global-status-report/ (Accessed 28 January 2019).
[2] D.O. Akinyele, R.K. Rayudu, N.K.C. Nair, Renew. Sustain. Energy Rev. 48 (2015) 112–139.
[3] Y. Tian, C.Y. Zhao, Appl. Energy 104 (2013) 538–553.
[4] M. Onasanya, An Evaluation and Development of the Potentials of Photovoltaic Systems for Water Pumping and Electricity Services in Rural Areas of Nigeria. PhD Thesis, Institute of Energy and Sustainable Development De Montfort University, 2017
[5] E.C. Ikejemba, P.B. Mpuan, P.C. Schuur, J. Van Hillegersberg, Renew. Energy 102 (2017) 234–240.
[6] A. Kassem, K. Al-Haddad, D. Komljenovic, Renew. Sustain. Energy Rev. 80 (2017) 75–91.
[7] K.M. Powell, K. Rashid, K. Ellingwood, J. Tuttle, B.D. Iverson, Renew. Sustain. Energy Rev. 80 (2017) 215–237.
[8] I. Purohit, P. Purohit, Renew. Sustain. Energy Rev. 78 (2017) 648–667.
[9] J. Shah, S.K. Gupta, Y. Sonvane, V. Davariya, Renew. Sustain. Energy Rev. 77 (2017) 1343–1348.
[10] R. Olabomi, A.B. Jaafar, M.N. Musa, S. Sarip, A. Ariffin, Renew. Sustain. Energy Rev. 73 (2017) 215–224.
[11] W. Ratismith, Y. Favre, M. Canaff, J. Briggs, Appl. Energy 200 (2017) 39–46.
[12] G. Gavagnin, D. Sánchez, G.S. Martínez, J.M. Rodríguez, A. Muñoz, Appl. Energy 194 (2017) 108–122.
[13] S. Lv, W. He, D. Hu, J. Zhu, G. Li, H. Chen, M. Liu, Energy Convers. Manage. 143 (2017) 459–469.
[14] A. Rezania, L.A. Rosendahl, Appl. Energy 187 (2017) 380–389.
[15] M. Thirugnanasambandam, S. Iniyan, R. Goic, Renew. Sustain. Energy Rev. 14 (1) (2010) 312–322.
[16] V.S. Reddy, S.C. Kaushik, K.R. Ranjan, S.K. Tyagi, Renew. Sustain. Energy Rev. 27 (2013) 258–273.
[17] H. Price, E. Lupfert, D. Kearney, E. Zarza, G. Cohen, R. Gee, R. Mahoney, J. Solar Energy Eng. 124 (2) (2002) 109–125.
[18] O. Behar, A. Khellaf, K. Mohammedi, Renew. Sustain. Energy Rev. 23 (2013) 12–39.
[19] H.L. Zhang, J. Baeyens, J. Degrève, G. Cacères, Renew. Sustain. Energy Rev. 22 (2013) 466–481.
[20] M.K. Gupta, S.C. Kaushik, K.R. Ranjan, N.L. Panwar, V.S. Reddy, S.K. Tyagi, Renew. Sustain. Energy Rev. 50 (2015) 567–582.
[21] S. Suman, M.K. Khan, M. Pathak, Renew. Sustain. Energy Rev. 49 (2015) 192–210.
[22] M.A. Sabiha, R. Saidur, S. Mekhilef, O. Mahian, Renew. Sustain. Energy Rev. 51 (2015) 1038–1054.
[23] J. Khan, M.H. Arsalan, Renew. Sustain. Energy Rev. 55 (2016) 414–425.
[24] A. Modi, F. Bühler, J.G. Andreasen, F. Haglind, Renew. Sustain. Energy Rev. 67 (2017) 1047–1064.
[25] R. O'Hegarty, O. Kinnane, S.J. McCormack, Solar Energy 135 (2016) 408–422.
[26] S. Abdelhady, D. Borello, E. Tortora, Energy Convers. Manage. 88 (2014) 872–882.
[27] M. Liu, N.S. Tay, S. Bell, M. Belusko, R. Jacob, G. Will, W. Saman, F. Bruno, Renew. Sustain. Energy Rev. 53 (2016) 1411–1432.
[28] M. Seitz, P. Cetin, M. Eck, Energy Procedia 49 (2014) 993–1002.
[29] M. Alguacil, C. Prieto, A. Rodríguez, J. Lohr, Energy Procedia 49 (2014) 21–29.
[30] W.G. Le Roux, T. Bello-Ochende, J.P. Meyer, Renew. Sustain. Energy Rev. 28 (2013) 677–690.
[31] S.C. Yu, L. Chen, Y. Zhao, H.X. Li, X.R. Zhang, Energy Convers. Manage. 94 (2015) 68–83.
[32] E. Okoroigwe, A. Madhlopa, Renew. Sustain. Energy Rev. 57 (2016) 337–350.
[33] J.D. Nixon, P.K. Dey, P.A. Davies, Energy 35 (12) (2010) 5230–5240.
[34] D. Barlev, R. Vidu, P. Stroeve, Solar Energy Mater. Solar Cells 95 (10) (2011) 2703–2725.
[35] B.J. Alqahtani, D. Patiño-Echeverri, Appl. Energy 169 (2016) 927–936.
[36] C.K. Ho, B.D. Iverson, Renew. Sustain. Energy Rev. 29 (2014) 835–846.
[37] List of operational solar thermal power stations. https://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations. (Accessed 25 January 2019).
[38] R.A. Guedez, A Techno-Economic Framework for the Analysis of Concentrating Solar Power Plants With Storage. Doctoral Thesis, KTH Royal institute of Technology, Industrial Engineering and Management, Department of Energy Technology, Sweden, 2016.
[39] L. Freris, D. Infield, Renewable Energy in Power Systems, 1st ed., John Wiley and Sons Ltd., West Sussex, UK, 2008.
[40] J. Twidell, T. Weir, Renewable Energy Resources, 2nd ed., Taylor and Francis, Abingdon, Oxon, 2006.
[41] D.O. Akinyele, R.K. Rayudu, Sustainable Energy Technologies and Assessments 8 (2014) 74–91.
[42] A. Fritsch, C. Franstz, R. Uhlig, Solar Energy 177 (2019) 155–162.
[43] M. Abbas, N.K. Merzouk, Techno economic study of solar thermal power plants for centralized electricity generation in Algeria, in: Proc: 2nd International Symposium on Environment-Friendly Energies and Applications (EFEA), 2012, 179–183.
[44] M.W. Haynes, A. Gunawan, S.K. Yee, Techno-economic comparison between conventional and innovative combined solar thermal power and desalination methods for cogeneration, Proc: Power Conference (POWERCON) (2018) 1–8.
[45] J.H. Lim, G. Nathan, B. Dally, A. Chinnici, Techno-economic assessment of a hybrid solar receiver and combustor, Proc: AIP Conference (2016) 1–8. , http://dx.doi.org/10.1063/1.4949167, 1732,070020.
[46] N.T.U. Kumar, A. Martin, Desalin. Water Treat. 98 (2017) 16–30.
[47] S. Thaker, A.O. Oni, A. Kumar, Energy Convers. Manage. 153 (2017) 423–434.
[48] Electric power consumption (kWh per capita) in Nigeria. http://www.tradingeconomics.com/nigeria/electric-power-consumption-kwh-per-capita-wb-data.html. (Accessed 22 November 2018).
[49] N.I. Nwulua, O.P. Agboolab, Int. J. Therm. Environ. Eng. 3 (1) (2011) 15–20.
[50] J. Kennedy-Darling, N. Hoyt, K. Murao, A. Ross, The Energy Crisis of Nigeria: An Overview and Implications for the Future, The University of Chicago, Chicago, 2008775–784.
[51] Stephen Ogunyiola. ''Energy Crisis In Nigeria.'' http://perpetualminds.com/2011/10/03/energy-crisis-in-nigeria/. (Accessed 25 January 2019).
[52] A.S. Sambo, B. Garba, I.H. Zarma, M.M. Gaji, J. Energy Power Eng. 6 (7) (2012) 1050.
[53] Electric Power Investors' Forum by Bureau of Public Enterprises (BPE). Power Generation (Status and Outlook). Presidential taskforce on power. https://studylib.net/doc/8304653/power-generation-status-and-outlook. (Accessed 22 November 2018).

[54] Electricity on demand. National Electricity Regulatory Commission http://www.nercng.org/index.php/contact/discos. (Accessed 25 January 2019).
[55] M.S. Adaramola, O.M. Oyewola, ARPN J. Eng. Appl. Sci. 6 (2) (2011) 82–86.
[56] D.A. Fadare, Pac. J. Sci. Technol. 9 (1) (2008) 110–119.
[57] A.S. Sambo, Renewable energy development in Nigeria, Energy Commission of Nigeria paper presented at the World's Future Council and Strategy Workshop on Renewable Energy (2010) (Accessed 25 January 2019) http://area-net.org/wpcontent/uploads/2016/01/E._BalaNigerian_Energy_Commission_RENEWABLE_ENERGY_DEVELOPMENT_IN_NIGERIA.pdf.
[58] C.G. Monyei, A.O. Adewumi, M.O. Obolo, B. Sajou, Renew. Sustain. Energy Rev. 81 (1) (2017) 1582–1601.
[59] D. Yergin, S. Gross, Energy for Economic Growth: Energy Vision Update 2012 (Industry Agenda), World Economic Forum, 2012 http://www3.weforum.org/docs/WEF_EN_EnergyEconomicGrowth_IndustryAgenda_2012.pdf (Accessed: 25/01/2019).
[60] V.A. Prisyazhniuk, Appl. Therm. Eng. 28 (2) (2008) 190–194.
[61] O. Babatunde, D. Akinyele, T. Akinbulire, P. Oluseyi, Renew. Energy Focus 24 (2018) 16–27.
[62] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, 4th ed., John Wiley & Sons, 2013.
[63] X. Ju, C. Xu, Y. Hu, X. Han, G. Wei, X. Du, Solar Energy Mater. Solar Cells 161 (2017) 305–327.
[64] J.P.N. Bootello, S.V. Rubia, L.S. Gallar, L.F. Calderon, Manageable hybrid plant using photovoltaic and solar thermal technology and associated operating method, in, Google Patents, 2012.
[65] M.A. Green, J. Zhao, A. Wang, S. Wenham, IEEE Electron. Device Lett. 13 (1992) 317–318.
[66] S.A. Kalogirou, Solar Energy Engineering: Processes and Systems, 2nd ed., Academic Press, 2013.
[67] Parabolic Trough Power Plant. https://www.mtholyoke.edu/wang30y/csp/PTPP.html. (Accessed 28 January 2019).
[68] G.W. Treadwell, N.R. Grandjean, F. Biggs, J. Solar Energy Eng. 103 (2) (1981) 98–104.
[69] Y. Lechon, C. de la Rứa, S.Ã. Rosa, J. Solar Energy Eng. 130 (2) (2008) 021012.
[70] D.W. Kearney, H.W. Price, Solar thermal plants-LUZ concept (current status of the SEGS plants), Proceedings of the Second Renewable Energy Congress vol. 2 (1992) 582–588.
[71] Concentrated Solar Power. http://www.solarcellcentral.com/csp_page.html. (Accessed 25 January 2019).
[72] M.R. Riaz, J. Eng. Power 98 (3) (1976) 375–383.
[73] R. Buck, T. Brauning, T. Denk, M. Pfänder, P. Schwarzbözl, F. Tellez, J. Solar Energy Eng. 124 (1) (2002) 2–9.
[74] M. Schmitz, P. Schwarzbözl, R. Buck, R. Pitz-Paal, Solar Energy 80 (1) (2006) 111–120.
[75] S.S. Mathur, T.C. Kandpal, B.S. Negi, Study of concentration characteristics and performance evaluation of a linear Fresnel reflector, in: Proc. of National Solar Energy Conv New Delhi: Tata McGraw Hill publishing Co., 1988, 263–270.
[76] C.J. Dey, Sol Energy 76 (2004) 243–249.
[77] D.J. Reynolds, M.J. Jance, M. Behnia, G.L. Morrison, Solar Energy 76 (1) (2004) 229–234.
[78] P. Doron, A. Kribus, J. Solar Energy Eng. 119 (1) (1997) 68–73.
[79] E. Wäckelgård, Solar Energy Mater. Solar Cells 56 (1) (1998) 35–44.
[80] G.M. Babu, T. Srinivas, K.V.R. Naidu, Int. J. Sci. Eng. Res. 4 (2013).
[81] J.S. Hseih, Solar Energy Engineering, Illustrated edition, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1986.
[82] P.L. Singh, R.M. Sarviya, J.L. Bhagoria, 2008 March. Improvement in thermal performance of the absorber for linear Fresnel solar concentrating collector. In Proceedings of the 15th International Conference on New Horizons of Mechanical Engineering (pp. 18–20).
[83] M.d.K.A. Khan, Renew Energy 7 (1999) 603–608.
[84] P.L. Singh, S. Ganesan, G.C. Yadav, Renew. Energy 18 (3) (1999) 409–416.
[85] N.D. Kaushika, K.S. Reddy, Energy Convers. Manage. 41 (7) (2000) 713–726.
[86] H. Hijazi, O. Mokhiamar, O. Elsamni, Alexandria Eng. J. 55 (1) (2016) 1–11.
[87] S.C. Kaushik, R.D. Misra, N. Singh, Int. J. Solar Energy 20 (4) (2000) 239–253.
[88] C. Koroneos, T. Spachos, N. Moussiopoulos, Renew. Energy 28 (2) (2003) 295–310.
[89] Non Grid Electrification Policy Guidelines 2012, Department of Energy. http://www.energy.gov.za/files/policies/electrification/Non-grid%20policy%202009.pdf. (Accessed 26 September 2017).
[90] A.S. Sambo, Electricity from renewable energy resources for remote locations: a case for solar and wind energy, Keynote Address at the One-Day National Workshop on Solar and Wind Electricity for Remote Locations, held at the Niger Delta Wetlands Centre (2006) . (Accessed 25 January 2019) http://www.africanpowerplatform.org/resources/reports/west-africa/nigeria/450-electricity-from-renewable-energy-resources-for-remote-locations-a-case-for-solar-and-wind-energy-in-nigeria.html.
[91] National Energy Policy 2003, Energy Commission of Nigeria. http://wacee.net/getattachment/21cca4e4-ef1b-4c59-8501-98b3e8624b88/National_Energy_Policy_Nigeria.pdf.aspx. (Accessed 26 September 2017).
[92] Renewable Energy Policy Guidelines 2006, Federal Ministry of Power and Steel. http://iceednigeria.org/backup/workspace/uploads/dec.-2006.pdf. (Accessed 26 September 2017).
[93] Draft National Renewable Energy and Energy Efficiency Policy (NREEEP) 2014, Energy Commission of Nigeria. http://www.power.gov.ng/download/NREEE%20POLICY%202015-%20FEC%20APPROVED%20COPY.pdf. (Accessed 26 September 2017).
[94] Electric Power Sector Reform Act 2005. http://rea.gov.ng/download/electric-power-sector-reform-act-2005/. (Accessed 26 September 2017).
[95] Stefan Bouzarovski, Neil Simcock, Energy Policy 107 (2017) 640–648, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2017.03.064. (Accessed 26 September 2017).
[96] Sustainable Development Goals. http://www.un.org/sustainabledevelopment/sustainable-development-goals/. (Accessed 26 September 2017).
[97] D. Akinyele, J. Belikov, Y. Levron, Energies 10 (11) (2017) 1760.
[98] Nigerian Oil and Gas Industry Content Development Act, 2010. https://assets.kpmg.com/content/dam/kpmg/ng/pdf/tax/nigerian-oil-and-gas-industry-content-development-act.pdf. (Accessed 26 September 2017).
[99] Industrial Development (Income Tax Relief) Act as amended. https://www.lawyard.ng/wp-content/uploads/2016/01/INDUSTRIAL-DEVELOPMENT-INCOME-TAX-RELIEF-ACT.pdf. (Accessed 26 September 2017).
[100] Solar thermal for utilities and industries. https://www.e-education.psu.edu/eme811/node/682. (Accessed 08 January 2019).