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Review

Barriers and Solutions for Increasing the Integration of Solar Photovoltaic in Kenya's Electricity Mix

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Abstract: Currently, Kenya depends mainly on oil, geothermal energy and hydro resources for electricity production, however all three have associated issues. Oil-based electricity generation is environmentally harmful, expensive and a burden to the national trade balance. The rivers for hydropower and their tributaries are found in arid and semi-arid areas with erratic rainfall leading to problems of supply security, and geothermal exploitation has cost and risk issues amongst others. Given these problems and the fact that Kenya has a significant yet underexploited potential for photo voltaic (PV)-based power generation, the limited—although growing—exploitation of solar PV in Kenya is explored in this paper as a means of diversifying and stabilising electricity supply. The potential for integration of PV into the Kenyan electricity generation mix is analysed together with the sociotechnical, economic, political, and institutional and policy barriers, which limit PV integration. We argue that these barriers can be overcome with improved and more robust policy regulations, additional investments in research and development, and improved coordination of the use of different renewable energy sources. Most noticeably, storage solutions and other elements of flexibility need to be incorporated to balance the intermittent character of electricity generation based on solar PV.

Keywords: technical; economic; institutional; policy; pumped hydro storage

1. Introduction

Nations in the developed world are transitioning towards the use of renewable energy sources (RES) as the main resource for meeting energy needs because of its potential to address issues of climate change [1]. As applications in the economically developed countries have helped to drive down cost, low and middle-income countries are also increasingly looking towards RES. Up until 2008, however, most countries had not included PV technology into their electricity generation mix [2]. One of the reasons is that PV technology lacked cost competitiveness when compared to other RES like wind power as well as when compared to power generation based on fossil fuels.

In general, in terms of installations, fossil fuel-based technologies have had an upper hand over PV on a global scale. Concerns, however, have mounted over the steady increase of greenhouse gas emissions, which has been prompting governments to adopt planning practices and policies [3] as well as subsidies favouring RES [4]. Such concerns as well as reductions in cost of PV technology have resulted in increased uptake and technology development in parallel.

The cost of PV systems in Germany for example, has been declining steadily and significantly over the past decade; this is attributed to the rapid technological development spurred by government subsidies [5]. Installed costs between 2006 and 2013 declined by an average of 16% per year. By the first quarter of 2017, the typical cost of solar PV in typical roof top applications had fallen to 1640 EUR per kWp from over 5000 EUR per kWp in 2006 [6].

This decrease in installation cost took place as installed capacity increased in the same time period. By the end of 2018, 1.5 million rooftop installations had thus been installed in Germany [7]—a country of approximately 42 million households [8].

Concurrently, the development of PV technology that resulted in increased efficiency from 15% to over 30% [9]. The decreasing module costs combined with increasing efficiencies have resulted in a compound decrease in the cost of electricity from PV modules. Consequently, in the global context, PV has become much more competitive and the cumulative capacity of PV technology has increased significantly [10].

The development has been uneven across the globe though. In a study by [11], the current status and outlook of RES in Morocco was assessed. Morocco has exceptional good potential for the exploitation of particularly PV, but also good prospects for wind power—two technologies already adopted in the country. In the study, challenges and barriers to the development of RES and the national strategy for energy security and how the challenges will be met was evaluated using time series method. Results of the study showed that in the long term, towards 2030, wind and solar power can be injected without creating constraints of transit on the solar and wind power.

Kenya, on the other hand is neither as ambition nor as successful in terms of PV development in spite of a good solar radiation. Data show that the total installed PV capacity in Kenya was only about 50.25 MWp as of 2019 [12]. This capacity is marginal compared to the total installed power production capacity of approximately 5000 MW in Kenya. PV is projected to grow at 15% annually [12] in Kenya mainly attributed to the decreasing prices and PV thus becoming more competitive, but this is still marginal compared to potentials, and in many case developments is on off-grid systems. For these applications, in addition to wishing to save money, consumers like the idea of being autonomous [13]—a motivational factor also seen in e.g., Denmark, where PV owners may even opt for costly storage systems to increase their level of electricity autonomy [14].

While a 15% annual increase in other areas would seem high, it does, however, not suffice for a transition as this expansion rate would require many decades of installations. Also, concurrently, an increase in income and a process of urbanization is generating increases in fossil fuel usage in Kenya [15] that also needs to be balanced through increased RES exploitation. Besides, the peak demand for electricity increased by 3.6% from 2018 to 2019, and the peak is projected to increase from 1802 MW in 2018 to 15,000 MW by 2030 [12]. More RES development is thus needed and any barriers have to be overcome.

In fact, the Kenyan electricity generation mix (See Figure 1) shows that fossil fuels only provided approximately one quarter of the electricity while hydropower and geothermal had even more significant shares of approximately 30% each. Thus Kenya is heavily supplied by RES as it is.

Kenya has a high potential for the use of geothermal energy, with potentials to increase from currently about 200 MW up towards 10 GW [16]. The exploitation faces several challenges however including rising investment charges, increasing resource exploration and expansion risks, land-use conflicts, inadequate expertise, and high investment in grid infrastructure due to long distances from geothermal sites to existing load centres [17].

Hydropower in Kenya is mainly in the form of dammed hydro power plants with production susceptible to drought. This results in a less-than-optimal robustness and outright load shedding [18]. Pumped hydro storage could provide more flexibility by also enabling also excess generation from wind and PV to be stored for later use. Wind and PV could thus assist Kenyan hydropower and making it more robust against drought.

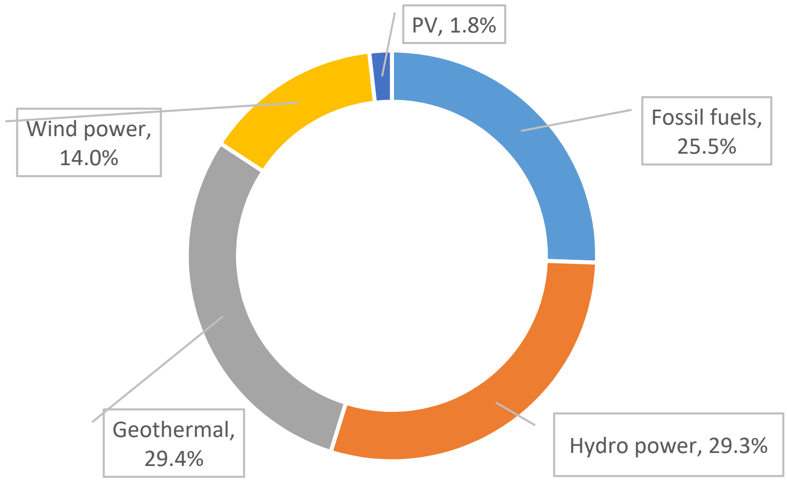

Figure 1. Kenyan electricity production mix shares in 2019. Based on data from [12].

Also, both hydropower and geothermal projects are characterised by long lead-times, thus in spite of potentials, these may not be adequate to fill the projected production gap.

Thus, as it is—and also combined with other constraints—the electricity system in Kenya suffers from frequent power outages. In a typical month, firms and homesteads connected to the grid experience on an average about six power outages, each lasting approximately five hours [19]. The economic cost of power interruptions is assessed to be about 7.1% of the power distribution companies' sales. Power outages therefore have a significant economic cost on businesses [19] and in turn on the Kenyan society.

Kenya has a large potential for PV since it is located near the equator, which provides it with a high insolation [18]. The insolation levels in Kenya and the large rural population is a stimulant for the penetration of solar power. According to [20] about 70% of the land area in Kenya has the potential of receiving approximately 5 kWh/m^2/day throughout the year with an annual mean radiation of 6.98 kWh/m^2.

A literature survey on the integration of PV in the electricity generation mix reveals, however, that focus is predominantly on Europe and United States of America. Little attention has been paid to emerging economies such as Kenya where electricity production and demand is expected to grow considerably in the coming years. Besides, there is room for adopting an infrastructure capable of meeting the future power demands using RES from the outset—and given the resource availability—notably PV.

Also, no study has highlighted the potential of and possible barriers to solar PV generation where hydropower already exists. Studies on PV in Kenya have a leaning towards ensuring access to electricity in areas located far away from the national grid as opposed to grid-connected projects [21,22]. This of course limits the analyses of interplay with hydropower. The only exceptions to off-grid analyses to date are viability studies in South Africa [23] and a review focussing on the development of mini-grids [24]. This paper therefore focuses on the prospects of balancing grid-connected PV systems with hydropower generation.

In spite of the demonstrated large potential of PV utilisation in Kenya, current exploitation is still limited, and projections show a modest growth that may not even match the increase in electricity and general energy consumption. Also, a predominant focus in the existing studies on Kenya is on the potential of PV as a source of renewable energy from a technical perspective and with a particular focus on stand-alone applications. While other countries—especially more economically developed—already target an increased PV exploitation even with poorer solar insulation conditions than Kenya, the country is still lagging behind in this respect. To exploit the potential more thoroughly, there is need for proper analysis of the opportunities and barriers for integration of PV in Kenya's electricity generation mix. The scope of this paper is therefore to analyse the potentials and barriers for deployment of PV technology in Kenya's electricity generation mix.

The paper is based on a review of the existing knowledge within the field, which is subsequently synthesized to provide a multifaceted perspective on opportunities and barriers to grid-connected PV in Kenya. The paper does not investigate off-grid PV systems.

2. Materials and Methods

The paper is based on existing literature as well as primary data collection from selected cases of grid-connected solar PV that have either recently been added to the national grid or is in the process of being connected in Kenya.

2.1. Literature Survey

The literature survey included a systematic four-step literature review where Scopus was used to locate the published literature.

In the first step, a combination of keywords was identified as follows: ("barriers" OR "opportunities") AND "PV". This combination was searched for in the abstracts, titles and keywords of the publications from 2012 to 2020 yielding 264 journal papers. Note that the search was not restricted to Kenya but yielded results from analyses worldwide to capture barriers and opportunities more generally.

In the second step, each publication was evaluated for its relevance to the integration of PV systems in the electricity generation mix, based on the abstract, title and keywords. If a publication had relevance, it was eligible for inclusion in the third step. This resulted in 102 journal papers.

In the third step, the full texts were evaluated in detail for their relevance to the barriers and opportunities for integration of PV technology in Kenya's electricity generation mix. This procedure ensured that no relevant information was missed from the publications. If a study addressed any kind of opportunity or barrier to the diffusion, it was included for analysis in the fourth step. Consequently, this resulted in 46 journal papers.

2.2. Analytical Framework

Barriers to renewable energy technology penetration in general and to PV technology specifically are global phenomena, and appear quite similarly in the literature, with only some country or technology-specific differences. Child et al. [25] has categorized major barriers to renewable energy technology penetration in six categories: "market failure/imperfection, market distortions, economic and financial, institutional, technical, and social, cultural and behavioural".

Some of the barriers noted by [25] include limited access to information, a bias for established energy resources, financial barriers, the circumstance that externalities are not factored into the decision-main process, lack of training, and a lacking acceptance [26].

Hvelplund has paid extensive attention to ownership [27,28] as a barrier and as an incentive for the advancement of energy technologies, however in our assessment we found little indication of the impacts of ownership in terms of acting as a barrier or opportunity. Some anecdotal evidence exists in terms of what type of actors have adapted PV technology in Kenya—but mainly on off-grid applications.

Also, not all the barriers identified by [25] are relevant or applicable in the Kenyan context. These categories of barriers and opportunities for success were therefore revisited and updated to make them relevant in the Kenyan context. Consequently, the range of barriers constraining the deployment of PV was categorized into technological, economic, institutional and policy as shown in Figure 2. This categorization is applied as the analytical framework.

As the fourth step in this analysis, the four categories of barriers and opportunities identified in the analytical framework presented in Figure 2 were evaluated. In addition to the literature search and analysis of other secondary materials such as government reports, conference papers and peer reviewed articles, this paper draws on in-sights from case studies on the Garissa solar PV project and the UNDP solar PV project—both in Kenya. The first author also draws on first-hand experience with installation of PV systems in the western part of Kenya. The first author reflects on his practical experiences on barriers that limit the uptake of PV and the existing opportunities and how they apply on a national scale to enrich the content of this paper.

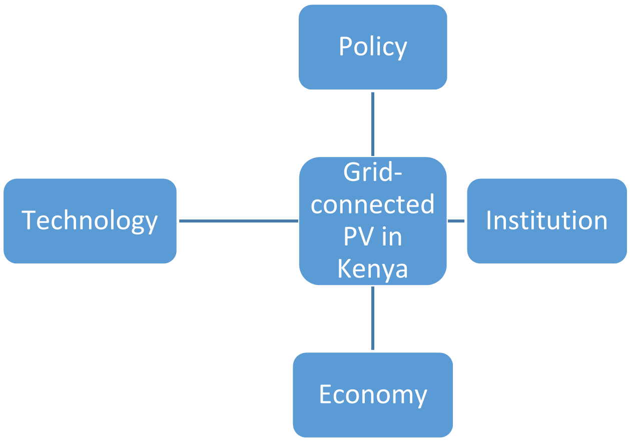

Figure 2. Analytical framework for assessing barriers and opportunities for increased integration of solar PV in Kenya.

As a last step in the analyses, international experience with pumped hydro storage is explored in order to show that it is technically and economically feasible to roll out this technology in Kenya.

3. Barriers to Increasing Integration of PV in Kenya

The barriers identified in the literature review are presented in this section—organised according to the analytical framework present in Section 2. These barriers are categorized into three: technological, economic and institutional barriers.

The advent of the PV technology in Kenya in the 1970s was mainly facilitated by donors and particularly in the 1980s, PV systems were donated to facilities such as health clinics that were off-grid [17]. During the implementation of PV in rural off-grid areas it was established that there was a market for PV technology beyond the scope of health clinics and off-grid missions [21]. Thus, within two years from 2000 to 2002, households increased the purchases of PV systems from 20% to 40% of total annual PV purchases. However, the benefits from the solar PV systems were mainly accrued by the rural middle class [28]. Consequentially, poorer rural households were sidestepped in terms of receiving subsidized PV systems [29].

With time, a focus on the rural affluent allowed the PV sector to be commercially viable without reliance on donors or subsidies. Specifically, in the 2000s, focus was on the middle-income segment, which was propelled by reduced costs of PV systems and a desire for the middle class to watch television [28]. These advances have led to the development of a considerable amount of PV systems being installed [30], however most of the development in Kenya has been in the form of stand-alone (i.e., off-grid) systems that are not connected to national grid. Thus, the PV market in Kenya has evidenced use of Solar Home Systems, which has been considered the most successful off-grid solar market in the developing economies [31].

3.1. Technological Barriers

Although PV technology has advanced significantly in the last decades, there are still several technical barriers to its adoption as highlighted in the literature. The quality of PV systems is of vital importance for its integration. Lack of adequate knowledge is a crucial barrier that may result in improper usage and inability to maintain the systems [13]. This may create a negative perception and prevent potential customers making a decision to adopt the systems.

A large technological challenge for PV in Kenya has been the lack of energy storage systems [32]. Meanwhile since Kenya relies largely on reservoir/dammed hydroelectric power supply, a PV-based pumped storage hydropower could offer an even more flexible solution to the variability of the residual production (demand minus non-dispatchable power production). Battery storage solutions also exist but the accompanying initial cost is high (though falling) for grid-connected systems hence research has pointed the need to look at development of hybrid systems combining solar PV with hydropower as a viable alternative option [33]. The storage requirement is of course dependent on both the composition of the rest of the electricity systems and on the share of PV. While a small share of PV can be integrated into the grid with no technical issues, large-scale integration of PV sets higher demands for the flexibility of energy systems.

Mathiesen at al. [34] identifies three phases of implementing RES. The first stage is the introduction phase where RES only marginally replaces production based on fossil fuels. The second stage is the large-scale integration phase where the integration of fluctuating renewables in the system becomes complex and where grid stability becomes an issue in the power system. The third stage is the full renewable energy phase with a complex system with suitable storage and conversion technologies to maintain the temporal balance of the energy system.

As the national Kenyan system is in the second phase—similar to most other countries in the world—the integration issues of large-scale integration are not faced yet, but a strong focus on PV will eventually bring the country there.

In this connection, the key technical issues that demand to be addressed when integrating solar PV on the grid include voltage level and point of common coupling, network voltage variations, power quality, voltage ride-through capability, reactive power compensation capability, frequency regulation capability and protection issues.

3.2. Economic Barriers

The main economic barrier for PV integration has been the high upfront cost and an unwillingness of banks to fund such investments [35]. The higher construction costs have previously made financial institutions more likely to perceive renewables as risky, lending money at higher rates and making it harder for utilities or developers to justify the investment. Perceptions of the (high) costs associated with solar PV can still be a barrier even if prices have come down considerably in recent years.

There have been efforts towards establishing the economic viability of solar PV in different regions of the world. A study focusing on the Middle East and North Africa regions concluded that rooftop PV systems were competitive with other energy producing plants in the region [33], however development has not followed suit. Nevertheless, a study in the Kenyan context confirms this. In [36] the authors used a levelised cost of energy evaluation and established that solar power in combination with other renewable energy generation technologies is competitive in relation to non-renewable energy. In spite of the high insolation levels, solar PV has mainly been used for off-grid application such as solar lanterns because of the high upfront investment costs of grid-connected solar PV systems [37]. However, currently, solar PV has been highly incentivized and prices have dropped significantly thus making it a viable option compared to diesel-fuel generators that are expensive to run [38].

Cost comparisons and competitiveness of solar PV with the conventional fossil fuels to electricity production are among the most significant barriers for adoption of solar PV in Kenya both for the utility company and for individual investors [17]. From the perspective of both the national utility company Kenya Power and Lighting Company (Nairobi, Kenya) and independent power producers, large-scale PV electricity generation without a well-functioning energy storage system maybe too expensive considering the fact these companies are also required to maintain the grid infrastructure and manage other running costs [31].

To mitigate these challenges, the incumbent could consider selling or leasing out PV energy storage systems, provide financing and grid connections or build a service relationship with individual investors. Once the domestic market grows, the installation costs will become cheaper; this could further be facilitated by training and certification of solar PV installers at the national level [39].

3.3. Institutional Barriers

The institutional barriers vary largely and are here grouped into four categories; (a) grid access, (b) research and development programmes, (c) university linkages and (d) policy experience from other African nations.

3.3.1. Grid Access

Kenya has an interconnected national electricity grid operated and run by the monopoly Kenya Power and Lighting Company Limited (Nairobi, Kenya). Unfortunately, the process of grid connection for new PV systems is long and complicated (that requires up to fourteen licensing steps) which discourages potential investment in PV power generation [18].

3.3.2. Role of Education, Training, Research and Development Programmes

Globally, China is a powerhouse for solar technology [40]. In 2001, China had thirty research institutes and universities that were working collaboratively to develop the materials used in PV cells [41]. Notably, key Chinese producers of PV manufacturing equipment have emerged with a number of firms being tasked with PV system design, technology research and development, manufacturing of the components as well as sales and after-sales service.

In Kenya, most solar PV firms have been involved in the government led rural electrification programme [42]. However, there is minimal research and development within the firms since most of them rarely devote a portion of their annual turnover to facilitate their technological capabilities and the competitiveness regarding PV [43]. Hence, in view of the extant literature, instances of research and development in the PV in Kenya are close to none.

In 2015, Maclean and Brass [44] noted that the Kenya Industrial Research and Development Institute is engaged in researching the development of low-carbon and climate-resilient technologies such as PV. The authors noted that Migori, Bungoma, Kirinyaga, Embu and Samburu were among the counties that were surveyed for low-carbon technologies. This is referred as a niche development for Kenya relevant to make affordable PV systems for off-grid rural areas. This study concluded that a policy brief should be developed to spur a pico solar market in Kenya. Pico refers to the smallest portable photovoltaic systems mainly typified by rechargeable battery.

3.3.3. University-Industry Linkages

Institutions of higher learning are instrumental players in both national and regional innovation systems [45]. In the recent past, universities have received substantial attention with regard to their role in innovation and spurring economic development. Universities are credited with major advances in scientific research and the creation of innovations with impact on the society.

Universities in Kenya have historically played a role in its National Innovation System also in development of RES. Strathmore Energy Research Centre (SERC)—a brainchild of Strathmore University in Nairobi—offers professional training, project development, and technical research in the renewable energy sector [36]. Since its inception in 2012, SERC has been at the forefront in implementing innovative pilot projects with the intention to promote RES into Africa. Trained technicians from SERC are able to do PV installation, repair and maintenance thereby raising awareness and contributing towards uptake of PV technology.

Furthermore, the centre for research on New and Renewable Energies at Maseno University has also been instrumental in promoting RES exploitation locally and regionally with special emphasis on rural application [44]. The centre focuses on harnessing bio-energy, geothermal, solar and wind energy.

The energy technology programmes offered in Kenyan universities are created to develop individuals with the capacity to address the national and global challenges in the energy sector. Therefore, this indicates that university-industry linkages exist and maybe utilized to foster increased integration of PV in the electricity generation mix.

3.3.4. Policy Experience from Africa

The African continent has a rich source of solar energy and in the recent years, PV has been becoming a viable alternative source of electricity for both small and large-scale application in Africa [42]. Like Kenya, solar PV deployment in most other countries in Africa has mainly been driven by rural (off-grid) electrification. As opposed to most of the African nations, Morocco saw the need for spurring PV on a larger scale for electricity generation at an early stage. In fact, a Moroccan integrated solar project was launched that comprised of solar and wind technologies that complement each other [46]. In addition, the Moroccan government commissioned a 500 MWp PV plant in 2018 [46].

In 2015, Rwanda was at an early stage of solar power integration according to [1]. At the time, there were at most eight companies which were mainly donor-driven and whose scope was to install solar systems in government hospitals and schools. According to the authors, there was a growing market for solar PV mainly among the private households.

Despite this, Rwanda possesses the highest grid connection in East Africa ahead of Kenya and Tanzania [1]. Nonetheless, there has been a tremendous growth in PV for off-grid Rwandan rural electrification since 2009 [28]. Further development of the technology was due to a strong focus on the Rwandan vision 2020 [47], which puts emphasis on renewable energy technology.

Besides, the Monetary Growth and Poverty reduction policy in Rwanda states that the government in collaboration with the private sector should facilitate the distribution and the sale of solar PV systems and further provide a regulatory environment that is conducive for the rapid integration of PV [47]. Experience from Rwanda and Morocco could be used to inspire policies in Kenya to help foster increased integration of solar PV in the country.

3.4. Political Barriers

Policy measures are of vital importance for large-scale introduction of PV. A lack of stability of incentives for the adoption of PV can be a significant barrier—for instance a sudden removal of existing subsidies or inconsistencies in policy measures.

Kenya has instituted policies meant to increase the integration of PV [1]. Particularly, among these policies is the Kenya Rural Electrification Master Plan [48], a Feed-in Tariff policy [49] and the Vision 2030 [50]. The government has also made a move towards ensuring that entrepreneurs willing to invest in solar PV are catered for [47].

As early as 2008, Kenya developed a feed-in tariff policy meant to ensure market stability for investors in PV. The feed-in tariff made it possible for independent power producers to deliver power from wind and hydro sources to the national grid. In 2012, the feed-in tariff policy was revised to also include solar power [37]. However, these policies have not translated to higher installed grid-connected PV capacity largely because the policies are not well coordinated during implementation or at worst, they are not implemented at all [1].

Under- or over-prioritization of investments in certain sectors in relation to others is usually not based on technical decisions but rather involves political choices and prioritizations. Large-scale PV projects are essentially large infrastructure projects that are typically highly political and that involve a multitude of actors with competing interests and negotiations across various levels. For example, [51] argue that the push for RE in Kenya is not necessarily being driven by environmental concerns, but rather by the need to provide access to electricity to the highest number of people within the shortest time possible. These authors highlight the tensions that come from pursuing the multiple objectives of ‘growth’, ‘inclusiveness’ and ‘sustainability’.

4. Pumped Hydro Storage Solution

This section discusses pumped hydro storage solution by reflecting on experiences from various countries which have similar conditions as Kenya. The importance of pumped hydro as a possible solution that can be replicated locally to meet electricity demand can therefore be proven since it has been applied in various countries with similar conditions as Kenya.

The shift from fossil fuel-fired power production to RES such as PV requires some form of storage or flexibility to cope with intermittency of the sources. A limitation with batteries is that they cannot offer multiple-hour storage capacity and discharge over a long time period. Moreover, batteries have a specific lifespan beyond which their performance is not guaranteed. Batteries also require ample housing space for large power output.

Pumped hydro storage (PHS) is a form of energy storage whereby gravitational potential energy of water is pumped from a lower reservoir to a higher one serve as a dispatchable reservoir to feed turbines on request [52]. PHS is the largest form of grid energy storage available; currently, PHS accounts for about 95% of all active and tracked storage [53]. The first PHS systems were commissioned in Alpine Switzerland, Austria and Italy in the 1890's. World-wide installed capacity stands at over 181 GW, of which about 29 GW are in the USA [52].

Modern PHS plants have a cycle efficiency of about 80% [54,55], and allow the utilization of excess electricity from base-load power sources (such as coal or nuclear) or fluctuating RES to be saved for use during periods of higher demand. Reservoirs used in these systems are generally smaller compared to conventional hydroelectric dams of similar power capacity and their generating periods are often less than half a day.

Chile has vast amounts of solar and wind resources which are increasingly being harnessed to replace fossil fuel generation. The impact of large scale integration of these variable RES for grid-level electricity storage was evaluated by [55]. In this study, a cost-based linear optimization of the Chilean electricity system was developed to analyse and optimize various RES generation, transmission and energy storage scenarios until 2050. Results of this study showed that for the base scenario of decommissioning of aging coal plants and no new coal and large hydro generation, the generation gap can be filled by PV, concentrated solar power and flexible gas generation resulting in a drop of 78% in carbon dioxide emissions. Integration of PV for on-grid storage increases the solar PV fraction which consequently leads to a 6% reduction in operation and investment costs by 2050 [55].

Switzerland was a pioneer in electricity generation and a European leader in power storage [56]. The country's mountains, extensive snows and glaciers favour development of hydro technology which is well developed and mature. As a result, hydro power generation from Switzerland is critical in western European electric power system supply backup and means of storage of reserve power [5,55]. Power management and storage are also critical towards achieving 100% renewable energy-based system in Switzerland. The country utilizes two different hydro storage systems; PHS and hydro systems with natural inflows to reservoirs that are subsequently feed to turbines on demand

A steady increase of the RES share in Australia's electricity mix is causing a move away from dependency on fossil fuels. A study by [57] focusing on the South West Interconnected System in Western Australia modelled several high penetration scenarios for renewables comprising wind and PV and PHS. The scenarios were examined using a chronological dispatch model restricting to technologies that were already deployed on a large scale i.e., greater than 150GW were utilized. Results obtained demonstrated that 100% penetration of wind and PV electricity is compatible with a balanced grid—though requiring PHS. Furthermore, with the integration of PHS, a RES share over 90% will still be allowed at a competitive electricity supply cost.

A case study by [58] based on Ometepe island, Nicaragua simulated a PHS and geothermal plant using HOMER software. The island was chosen because it has wind, solar and geothermal resources as well as an extinct volcano with a crater on its top that can serve as the upper reservoir for the PHS system. Different system configurations were demonstrated and the results obtained revealed that PHS technology is able to serve the base load of the system, therefore reducing the required installed capacity of other power resources as well as decreasing the storage requirements and excess electricity production.

Zimbabwe is among the African countries which rely on power imports to meet its energy needs which endangers the energy security of the nation. Several studies have been conducted to assess the feasibility of hybrid power generating systems that incorporate intermittent power sources such as PV with or without storage in order to maximize technical and economic feasibility. One such study by [59] made a techno-economic comparison between standalone wind or PV and hybrid PV/wind. The hybrid system was based on maximizing intermittent energy sources. Results obtained showed that the levelized cost of electricity was less than or equivalent to the local grid tariff. The study further revealed that the utilization of RES would boost energy security and reduce dependency on imported energy.

A 2000 MW PHS plant supported by a 300 MW PV plant is being constructed on the Osborne dam, river Odzi in the Manicaland province of Zimbabwe [60]. This is the first project of its kind in the country which will provide backup for the national power grid during peak hours when the available network capacity is insufficient. Peak demand in Zimbabwe is observed for 8.5 h in a day [61,62].

Evidently from the foregoing, PHS is a mature technology that has been tried and tested. Through coordination, a higher penetration of solar PV may be achieved by using hydropower to compensate for the fluctuations in PV output in Kenya. Consequently, there will be less disruptions in electricity supply since there is reliance on both solar and hydropower.

5. Modelling of Kenya's Future Electricity Grid

This section reviews modelling studies that have been conducted relating to the future of electricity grid in Kenya. Similar studies in selected African countries and outside of Africa are also reviewed.

PV as a technology for electrification of rural Kenyan communities was modelled in [21]. The results showed that interconnecting a number of solar minigrids into one common grid leads to better technical performance. Moreover, the more minigrids connected, the better the performance and the more the power available for the national grid for supply to consumers.

A system-level model of Kenya was presented in [2]. This was used to assess the combination of PV and hydropower to displace diesel-based power generation. The research tested various generation mixes for the years 2012 to, and results obtained showed the value of high penetrations of PV exceeded expected feed-in-tariff payments.

In the work of [62], a spatially explicit supply model was developed to seek for a least-cost PV electrification model to connect consumers that are not served by the national electric grid. Information from individual consumer demand was used to develop this model. It was concluded from the results obtained that PV minigrids can serve up to 17% of the country's population. This includes due consideration for latent demands—i.e., demands currently unmet but which either grid expansion or access to PV electricity may stimulate.

In another study by [63] a rural electrification spatial model for Kenya was developed to identify various approaches to meet electricity needs for various places in the country. The analyses considered both diesel-based generators, various renewable energy sources and expansion of the national grid. Results obtained showed that renewable energy sources can play a key role in meeting energy demand for rural consumers.

Another study conducted in Morocco by [64], an energy management algorithm was modelled and simulated using MATLAB/SIMULINK to serve the load. The system is a grid-connected PV-battery which can manage its energy flows via an optimal management algorithm. Results of this modelling showed that the load was well served in all cases by instant solar production.

In Tunisia, research by [65], a grid connected PV system was modelled using a command approach to function under normal conditions and Symmetrical Grid Voltage Dips (SGVD). In normal operation mode, the command developed increased the low solar voltage to a suitable level corresponding to the Maximum Power Point Tracking. Under the SGVD, the control strategy should ensure stable connection as long as possible and inject more reactive power to support the grid faults. The modelled control scheme in the various operation modes presented high performances in transient and permanent phased. The system improved safety of the overall system and increased the connection time.

Experience from outside Africa has demonstrated how a decentralisation of power production on cogeneration of heat and power plants [66,67] and wind power [68,69] reduce grid loading thus enabling weaker grids, leave capacity for transit if so needed while at the same time reduces grid losses [70]. These analyses are based on a combination of energy systems analyses [71] using the EnergyPLAN model [72,73] and transmission grid analyses taking into consideration hour-step analyses of the 150 and 400 kV transmission grid.

All in all, experience from the literature demonstrate that a decentral deployment of grid connected PV systems could benefit the energy system—though due concern of ancillary services is still required.

6. Discussion

This section discusses the key challenges facing integration of PV into Kenya's electricity generation mix, and also puts some of the issues into a wider perspective.

A key technical challenge for integration of PV technology is the temporal match with the demand; solar power is available during the day and there must be a viable way of harnessing it for use when the sun is not up. In Kenya, electricity generation in the form of pumped hydroelectric power generation is seen as a viable option to replace run-of-river hydroelectric power plants whose production in susceptible to drought which result in reduced electricity generation capacity as well as outright power outages.

As it is, the electricity system in Kenya suffers from frequent power outages that are well documented. In a typical month, firms and homesteads connected to the grid experience on average 6.3 power outages, each lasting approximately five hours [19]. The economic cost of power interruptions is approximately 7.1% of the firms' sales; power outages therefore have a significant economic cost on businesses [19] and in turn on the Kenyan society.

There has been less emphasis on solar PV in Kenya. Specifically, no study has highlighted the potential of and possible barriers to solar PV generation where hydropower already exists. Studies on PV in Kenya have a leaning to integrate PV with other technologies. For policy-makers and international organizations keen to reduce carbon emissions and dependence on imported fuels, the deployment of hydro resources alongside solar PV is a viable option for many sub-Saharan African countries. It is here important to note the role played by hydropower sources, which supply approximately 30% of the end-use electricity demand in Kenya.

Kenya has a great potential for pumped-hydro storage for the integration of PV [2]. Dammed hydro or even pumped hydro storage are both dispatchable and thus offering regulating capability to the power system. For pumped hydro storage, low-cost surplus off-peak electric power can be used to fill reservoirs which is subsequently released through turbines during periods of high electrical demand. The cost of pumping water can easily be met from the revenue generated from selling power during peak demand periods—even when factoring in the cycle losses. At any rate, with cycle efficiencies in the 70% to 80% bracket [74] and modest cost per size [75], pumped hydro systems are a good storage candidate for large-scale PV integration.

In colder climates where heating systems offer flexibility through system-integration, options are more diverse with the use of cogeneration of heat and power [70,76–78], heat pumps [79,80], heat storage [75] and smart energy systems [81–84] for the integration of renewables. The potential for this sectorial integration between heat and electricity is not so pronounced in warmer climates. Also, in the future, electric vehicles provide an opportunity for integrating PV power [35,85–87], however this solution comes with a cost barrier.

There are conflicting standpoints and expectations of policy makers and utilities that constitute institutional and policy barriers. Incumbent electricity companies in Kenya are likely to favour maintaining the status quo since they have made investments in the existing electricity generation system. This creates path dependency and lock-in effect [87]. Kenya Power has the sole monopoly of managing costs of connecting PV systems to the grid and they manage the grid single-handedly. At the same time, new forms of electricity generation such as PV generation try to break the lock-in and this clashes with the current Kenyan electricity regime that is mainly based on hydro, geothermal and fossil fuels. Resistance from the utility or other industry players can be sensed in the context of path dependence and lock-in, and therefore undermines integration of renewable sources of energy [36].

On the other hand, the supportive policies advanced by the Kenyan government towards renewable energy have contributed towards a growing interest among citizens related to solar energy. There is a range of different kinds of support instruments in use, such as a conducive environment for investment, innovative financing schemes, exemptions from value added tax and import taxes, standardized power purchase agreements and feed-in-tariffs which have led to the growth of PV market in Kenya [49].

These policies have raised the point that dynamic support structures for renewable energy technologies can aid in increasing their market penetration. A period of high subsidy may be particularly important to establish early growth in market share, but should be followed by adjustments in subsidies to prevent markets from growing too quickly. At the same time, [87] reminds that support must go beyond financial measures to be sustainable by offering training programs on operation and maintenance. Also, [87] found that one-off investment support or tax rebates were preferable to feed-in tariffs, as they were deemed more cost efficient and were likely to instil greater confidence in investors.

In addition, research institutions play a critical role in integration of PV systems through building of local capacity to handle installation, operation and maintenance of PV systems. As highlighted earlier, research and development has played a key in the advancement of PV technology in countries such as China. Kenya needs to invest more in research and development in order to scale up electricity generation from PV technology and therefore increase economic competitiveness of solar PV.

These linkages can be extended to collaborations between Kenya and the international community. In most African countries integration of solar PV systems (mainly small-scale) has been driven by donor-supported projects aimed at serving specific needs for electricity [1]. Historically, development of PV systems has been aided by the donor community which has facilitated acquisition of solar systems to local communities and institutions by providing the requisite resources. Arguably, availability of resources from PV actors from outside Kenya may also help scaling up of PV technology in the country. PV development in Kenya is also shaped by the market forces of demand and supply.

In terms of the proposed storage solution, PHS is already a well-established technology in several countries—and as our analyses show, it is also a technology that is applied or considered in conjunction with PV. The non-technical prospects of PHS in a Kenyan context have not been considered, but it is a technology that is traditionally owned and operated by larger players in electricity markets—power producers or transmission system operators e.g., Kenya Generating Company Limited and Kenya Transmission Company Limited could thus fit institutionally well into a system as the Kenyan with a strong central player in Kenyan Power and Lighting Company.

7. Conclusions

This paper has discussed the barriers and possibilities for overcoming these for the integration of PV technology in Kenya based on a literature review to achieve high installed capacities. Significant changes must occur in the Kenyan electricity sector. Most noticeably, storage solutions and other elements of flexibility need to be incorporated to balance the intermittent nature of electricity generation based on solar PV. This is particularly eminent for large-scale deployment of PV technology in Kenya. A complement between hydro and solar PV to address the storage challenge was proposed in this investigation.

Such a hybrid system represents a complete transformation from the current scenario. A variety of technical, economic, institutional, political barriers have been pointed out which currently restrict further increase of PV technology.

Some of the technological barriers identified include lack of adequate knowledge of PV technology and lack of energy storage systems or energy system flexibility to integrate PV. An important economic barrier identified is the high upfront costs and unwillingness of banks to fund PV investments. Some of the institutional and policy barriers identified are lack of stability incentives for adoption of PV and the long and complicated grid connection process.

These barriers can be overcome with robust policy regulations, additional investments in education, training, research and development, better regulation of the electricity sector and improved coordination between key actors.

While this analysis focused on the barriers for solar PV in the Kenyan grid system, the results may be applicable to other sub-Saharan African countries, many of whom are faced with the same challenges: growing demand for electricity, insufficient generating capacity, and long lead times and extensive financial investments required for planned generation projects. As a result, many countries have turned to short-term expensive solutions such as diesel plants. Further, the other characteristic—that may make solar PV a favourable option in Kenya such as abundant solar resource—is also present across the continent.

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