Sustainability-Oriented Framework for Design, Planning and Operations of Isolated Microgrids in the Era of Uncertainties

Onyema Nduka & Amirhossein Adib
Power Systems Research Group, Department of Electronic Engineering
Royal Holloway, University of London
United Kingdom

***Abstract*—Microgrids (MGs) have emerged as critical infrastructures for providing flexibility services to the main grid as well as accelerating electrification in regions with no access to the grid. Nevertheless, in some situations (especially for isolated microgrids (IMGs)), their immense benefits seem not to have been fully realised owing to inadequate planning and operations underpinned by few aspects of sustainability rather than a holistic and robust approach. Hence, this paper presents a region-agnostic and robust sustainability-oriented framework for the design, planning and operations of IMGs underpinned by sustainable engineering design principles and described by '9-Rs'. We propose that core sustainable engineering principles must be embedded right from the IMG project conceptualisation stage and not as an afterthought activity. Moreover, we argue that there is a need for robust involvement of several stakeholders in tackling one of the greatest challenges of recent times - the transition to sustainable energy for all. Other interesting findings are documented in this paper.**

***Index Terms*—Climate change, energy security, framework, microgrids, sustainability, uncertainties.**

I. Introduction

EVIDENCE suggests that the global climate is changing owing to anthropogenic activities that have resulted in increased emissions of greenhouse gases (GHG). This is supported by the observation of increased frequency and duration of events like wildfires, drought, desertification, flooding, extreme temperatures, etc [1]. Consequently, there is an urgency to limit the average global temperature rise in line with international agreements. This has motivated the push for deep decarbonisation of the electricity, transport and heat sectors [2]. While there are recorded successes in different countries, the deep decarbonisation of the electricity sector globally remains one of the most difficult sustainability challenges of the 21st century [3]. However, this decarbonisation challenge is paralleled by an ongoing crisis of basic energy access. As highlighted in Fig. 1, the global electrification gap is severely concentrated, with 85% of the unserved population residing in Sub-Saharan Africa [4].

Furthermore, factors such as population growth, ageing, climate change, pandemic, wars, the emergence of technologies like artificial intelligence and machine learning (leading to the need for AI data centres), electrification of transport and heat systems, digitalisation of health, education, commerce, entertainment sectors, etc., have continued to influence the growth of electricity demand globally. Moreover, the global uptake of technologies like electric vehicles (EVs) is still on an upward trajectory, which is favoured from an environmental sustainability context [5]. Fig. 2 provides a conceptual illustration of the sustainable power and energy systems challenge of recent times. The figure shows different factors that influence global electricity demand. On the other hand, the electricity generation sector is also influenced by factors such as technological advancement, resource availability, policies and regulations, climate change, electricity market forces, etc. Additionally, the transmission and distribution networks for several countries are obsolete, significantly constrained and require a meaningful upgrade for the achievement of the deep decarbonisation agenda. Such transformations while expensive provide a better alternative to full deployment of fossil fuel technologies whose impacts (in the context of climate change) can have serious consequences [3].

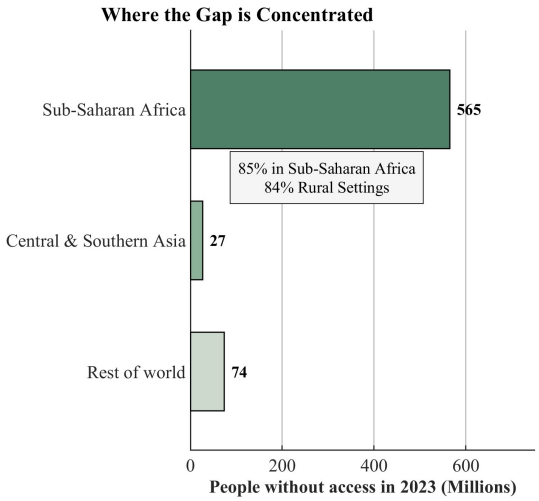

Fig. 1. Regional concentration of the global electricity access gap in 2023.

Moreover, while several expansion projects for the main grid are unfolding, it is unrealistic to adopt grid expansion for all scenarios - at least the prohibitive costs and time requirements are major setbacks [6]. MGs are indeed critical

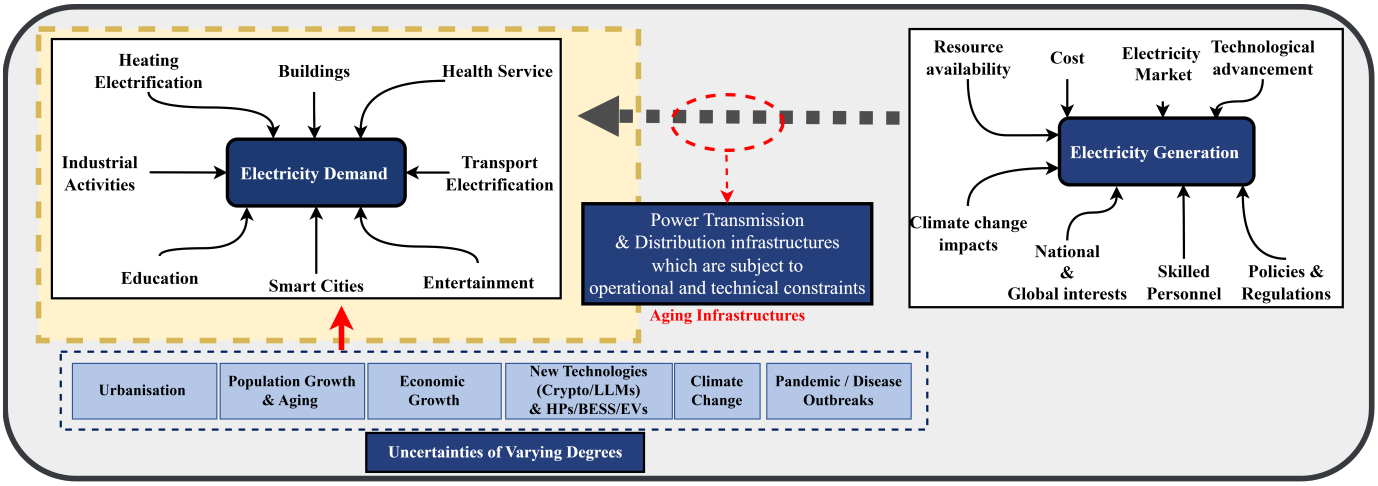

Fig. 2. Conceptualisation of the sustainable power and energy systems challenge.

infrastructures for providing electricity access to remote locations where grid expansion would be economically prohibitive. They also serve as a key enabler for high uptake of renewable energy sources (RES) like solar and wind, promoting EV and heat pump connections, etc. Moreover, it has been argued that the first electrical systems built by the famous inventor, Thomas Edison, were essentially MGs [7]–[9]. For completeness, an MG is an electrical network with distributed energy resources (DERs) and loads operating as a single entity either in isolation or whilst connected to the main grid. In comparison with the main grid, an MG has generation and distribution infrastructure but with no transmission system. For the purpose of this paper, an MG also encompasses a minigrid which is a term that has been popularised for rural electrification or off-grid projects. For certain regions, especially in the Global South, these MGs are critical infrastructures that significantly impact the economy and well-being of the people. Moreover, MGs have been deployed to provide electricity to hospitals, schools, rural communities, markets, hospitality sector, and humanitarian relief centres (such as refugee camps for war-impacted areas, natural disaster-impacted areas, etc.) in different regions of the world [10]–[15]. The role of MGs for EV charging [16] and provision of flexibility and resilience enhancement services [17] to the main grid have been well-documented.

Despite the numerous advantages of MGs previously outlined, it is not easy to design, operate and control such systems. For instance, there exist challenges in maintaining the frequency and voltage levels in an MG since there are multiple relatively small-sized DERs in such a network. Therefore, concepts such as voltage droop control are designed and implemented [16]. Such relatively small-sized electrical systems find it difficult to robustly detect and manage faults like the main grid due to their low short circuit capacity [18]. Also, such systems do not usually have the same quantum of spinning reserve as the main power grid and so dealing with overloaded conditions usually involve load shedding, especially for IMGs [19]. Beyond technical challenges, MGs for rural electrification are faced with economic viability issue as it is oftentimes difficult to achieve return on investment by imposing cost-reflective tariffs due to the limited economic activities and low purchasing power of people in such remote regions. In fact, some of these MGs for rural electrification are funded through grants from national governments and international agencies but the financial support does not usually extend to the operational and maintenance phase of the project [20]. Moreover, some existing MGs still rely heavily on fossil fuels such as diesel and petrol which have undesirable environmental impacts [21].

As discussed in [3], sustainable energy transition must consider not only the economic, environmental and social aspects but must extend to technical, regulatory and policy elements. However, the trend in engineering literature shows a limited focus on aspects of the sustainability pillars, e.g., environmental, economic, technical or their combinations. Ref. [22] presented a review of existing works on community MGs and how their resilience could be enhanced by leveraging technologies like energy storage and advanced control to improve energy security. Simply put, that review and framework proposed focused only on the technical element of sustainability. In [23], another framework strictly focused on the technical aspects of an MG was also presented; specifically, a hierarchical framework for managing RES-related uncertainties in MGs aimed at economic generation schedule was proposed. Cheap RE generators were supported by energy storage to meet the demand in the MG and where required, the dispatchable distributed generators (DGs) were brought online to ensure the security of supply was maintained in the MG. Also, Ref. [15] has explored the adoption of low-voltage AC and DC for rural electrification in Cambodia - comparing results in terms of costs, emissions, energy production and losses.

While the authors of this paper recognise the efforts of existing research works in the open literature, it is clear that robust frameworks for designing, planning and operating IMGs aimed at achieving the necessary and

sufficient conditions of sustainability do not exist until now. Specifically, we propose a region-agnostic and robust framework described by '9-Rs' for a sustainability-oriented IMGs. Our proposed framework is underpinned by classical sustainable engineering design principles - see example principles in Ref. [24]. This framework is useful to support MG developers/operators involved in the flexibility services business (to distribution network/system operators) as well as minigrids powering off-grid communities with a reasonable level of economic activities (and thus having reasonable load levels). To be clear, the framework can be tailored to any MG; however, not all the components would need to be enforced in that case. For instance, it is impractical to suggests reshaping of demand in a nanogrid or solar home system where the load is quite small and hence, low (or almost non-existent) flexibility capital.

Other sections of this paper are structured as follows: Sections II and III respectively provide an overview of an MG and give context to the concept of sustainability-oriented MG. In addition, Section IV discusses the critical role of MGs for facilitating the achievement of several United Nations Sustainable Development Goals while V presents the proposed framework. This is followed by the conclusion.

II. Overview of Microgrid

The architecture of an MG vary based on the distribution types such as alternating current (AC), direct current (DC) and hybrid AC-DC with each having its merits and limitations. For instance, a DC-MG does not require reactive power control, it avoids losses due to skin effect in conductors and requires less conversion stages if it is based on RE technologies with DC outputs such as solar photovoltaics. On the other hand, grounding and protection issues and non-standardisation exist in DC-MGs. Moreover, an MG can operate in either grid-connected or inslanded mode [25]. For the former, the MG interacts with the main grid allowing it to import and export power and thus serving as a flexibility asset. However, the picture is different for an IMG which must manage its own voltage and frequency with its relatively small-sized distributed generators. Consequently, an IMG must be carefully designed and planned to ensure it is able to withstand stressed operating conditions arising from overloading, faults or electrical component failures, extreme events, etc. Moreover, it must ensure to have almost no (or very minimal level of) brownout and power outages while remaining affordable to the customers [18], [19]. The figure below (see Fig. 3) is an illustration of the different components that make up an example IMG.

III. Sustainability-oriented microgrids

As experienced with some MGs in the Global South, a number of projects have failed to deliver on their predicted benefits owing to the neglect of one or more elements of sustainability in the design, planning and operations. A robust sustainability framework for an IMG must therefore go beyond the well-known three pillars (economic, environmental and social) to rigorously consider policy and politics, technical aspects, local knowledge (including lived experiences) and knowledge of the geographical location especially if the IMG is designed to be resilient to extreme weather events. Moreover, it is critical to draw from existing sustainable engineering design principles. These gaps form the basis of our proposed framework.

IV. Microgrids as key enabler to achieving a number of the sustainable development goals (SDGs)

MGs are strategically placed to significantly facilitate the achievement of several of the United Nations SDGs as they directly contribute to goals 7 (clean and affordable energy for all), 8 (good jobs and economic growth), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities) and 13 (climate action). For rural electrification and humanitarian relief efforts, they also contribute to SDG 6 (available and sustainable management of water and sanitation), etc. Their usefulness apply both to developed and developing economies. While it can be deployed to provide flexible services to developed economies with relevant electricity infrastructure (thereby aiding deep decarbonisation), for developing nations, it is a critical infrastructure to electrify off-grid regions, drive economic growth and improve the well-being of people (especially women and children) and other species on the planet. Hence, their relevance cannot be over-emphasised.

V. Proposed Framework

The proposed framework is shown in Fig. 4 and can be summarised as discussed below.

1) **Reduce**: this first step aims to reduce electricity demand (load). It applies the concept of elimination of (electrical) waste as far as reasonably practicable and it interlinks with principles '2' and '3' of [24]. It includes adopting nature-based solutions to eliminate the need for the use of electricity in some cases (e.g., natural method of cloth drying, proper ventilation that reduces the need for dehumidifiers and fans, etc). There is also a major place for retrofitting to boost energy efficiency and reduce waste.
2) **Reliable (electricity mix)**: this aspect of the proposed framework also draws from the principle of green engineering design (principles 1, 10 and 12) [24]. The idea is to leverage locally available renewable-based technologies to meet the demand as far as possible while also having in the electricity mix, other technologies that are dispatchable. For instance, as shown in [21], a system with an electricity mix comprising solar, wind, battery energy storage and diesel power plant is cheaper, environmentally friendly and secure in comparison with a system that relies on diesel alone. This is especially true if the RESs are utilised maximally and the diesel power plant is brought online only when absolutely necessary. In fact, [23] has proposed a two-level approach where the first level involved the use of renewables

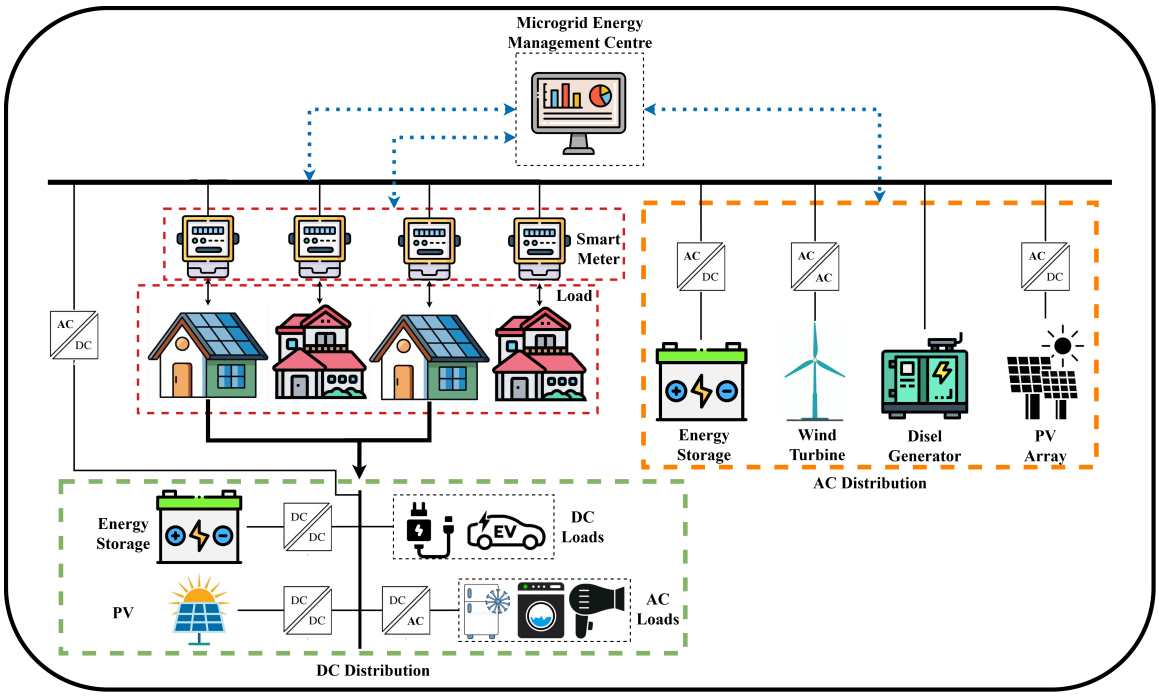

Fig. 3. An isolated microgrid.

and the second level allowed reasonable deployment of dispatchable power plants. Based on locally available resources, combined cycle power plants, biomass and hydrogen plants can be deployed alongside wind and solar power systems. For instance, the Global South must robustly consider a reliable electricity mix rather than solely focusing on environmental and economic components of sustainability. It is clear that sustainability is holistic and not reductionist.

3) **Reshape**: this aspect entails demand-side response (DSR) by design. For instance, it has been estimated that customers' electricity bills could be reduced and the British electricity system could become £3-8B per annum cheaper to operate by 2050 based on DSR [26]. In other words, at the IMG design and planning phase, the flexibility assets in the system must be identified and planned accordingly. Strategies on how to deal with any potential discomfort to customers must be considered from the design stage and not as an afterthought. Studies have shown that demand-side flexibility can be impacted by flexibility capital, the nature of the demand-side response scheme as well as the behaviour and perception of the participants [2]. Relying solely on customer response to a scheme influenced by factors such as pricing and incentives might be sub-optimum for an IMG. Moreover, user comfort and wellbeing must be given the attention it deserves to fully reflect the orientation towards sustainability - which among other things must be people-centric.
4) **Remove**: this step which involves the disconnection of non-critical loads must be minimised as far as possible but it is sometimes crucial for the survivability of the IMG to avoid a system collapse and total outage. This is usually described as load-shedding or power rationing. The responsibility for this lies with the IMG operator. Ideally, spinning reserve and redundancies need to be built into the system to ensure reliability, security and robustness; however, such redundancies are not infinite as they are constrained by costs and other factors. Therefore, it makes sense to include this step in the framework to avoid a reactionary approach.
5) **Restore**: in this step, the IMG's control and energy management system should automatically check after a specified interval (set by the MG operator) if it is technically feasible to re-engage a previously disconnected non-critical load without compromising the system's reliability and security.
6) **Replan**: many of the planning and operating approaches in the main grid have been adopted for the MG. While this is logical in certain aspects, it may be sub-optimal in others owing to IMG having a different architecture, size, level of volatility of load and variable generation, less redundancy, etc. For instance, tertiary-control level studies (involving economic dispatch and optimal power flows) in the main grid that assume frequency as fixed and a single slack bus as reference would not necessarily suffice for IMG due to the presence of relatively small-sized generators and rapidly changing loads. Hence, droop control and similar approaches are well-known in the MG literature [5].

Based on the previous work of the authors [1], we argue that these technical aspects must embed forecasts

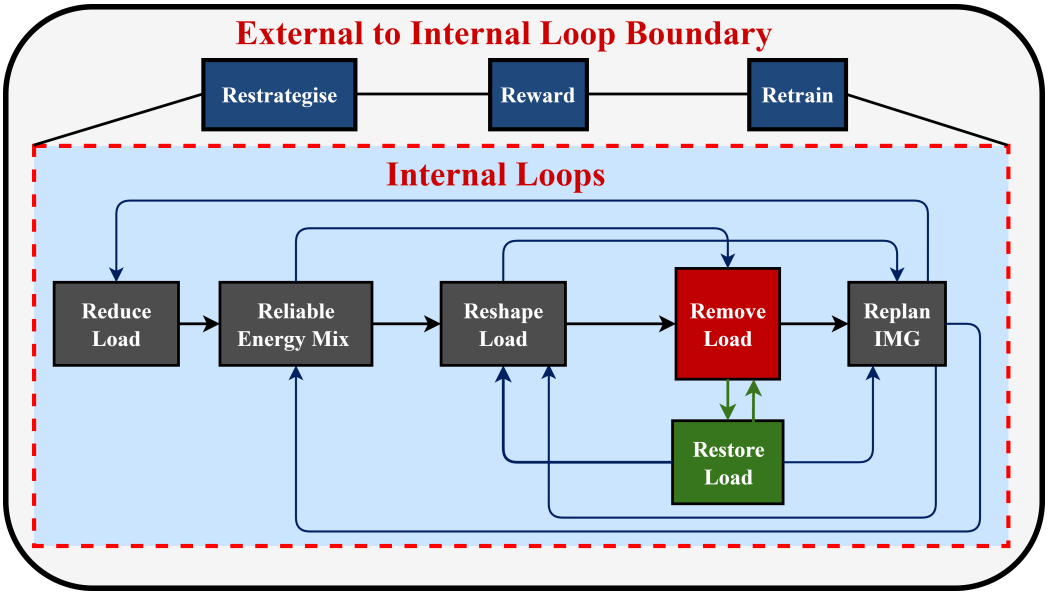

Fig. 4. Proposed sustainability-oriented framework for isolated microgrids.

of impacts of extreme weather and climate change-related events into the design, planning and operations of the IMGs to enhance security, resilience, reliability and safety. Moreover, data-driven approaches hinged on machine learning and artificial intelligence must be integrated into the planning and operations of IMGs. For instance, the weather, electrical load and renewable generation can be better predicted with these tools rather than relying on static approaches.

The authors of this paper have also demonstrated in Ref. [27], how hybrid physics and data-driven approaches could be leveraged for determining the optimal power flows in an IMG in the face of DG availability uncertainty.

7) **Restrategise**: this aspect demands that planning and funding provision for these IMGS must go beyond the commissioning phase to include robust long-term survivability plans. 'Big' players must seriously consider investing in the MG ecosystem. This must be anchored on the principle of service to humanity and not solely focused on profit maximisation [14]. This would reduce potential over-reliance of a particular region or country on foreign loans and grants for addressing the electricity infrastructure problems. The Dangote refinery built in Nigeria which has reduced the country's dependency on oil importation is clear proof that key players can transform a sector through bold and ambitious investments. The 'big investors' must consider investing in all sectors of the MG ecosystem ranging from the manufacturing of solar panels, inverters, batteries, etc., to recycling of these assets after their useful lifespan. All these would help to reduce environmental impacts that may accrue from poor-quality products and poor recycling.
8) **Retrain**: this involves the training and retraining of people on the entire MG ecosystem. As highlighted in [20], the absence of trained personnel in some regions can impact the durability of an MG and whether it serves up to the estimated useful life. Moreover, the training must go beyond installations to include repairs, reuse, recycle and different aspects of the circular economy of the MG. Moreover, custom-developed tools that incorporate regional knowledge must be fully explored. Indeed, there is no 'one-size-fits-all' and according to the tenets of sustainable engineering design, the purpose of the MG in a region must be specific, clear and made known to all stakeholders from the outset.
9) **Reward**: while the authors are aware of different financing schemes and business models for the MGs [14], [28], we argue that such business models must be innovation-centric and not solely profit maximisation oriented. Investors must think beyond quick return on investment to also consider other national and global challenges that may accrue from unsustainable practices to meet the energy needs of people. While economic growth must be pursued especially by developing nations, this must be balanced with all other elements of sustainability previously discussed. Hence, our framework proposes a carefully tailored and robustly implemented RIIO 3 (Revenue = Incentives+Innovation+Output) [29] or similar models in the MG ecosystem of several countries. Policymakers and regulatory agencies (especially in developing nations) must ensure that all loopholes to importation of inferior equipment for electrification are dealt with as these often lead to premature failure of MGs and hence increased electrical and electronic waste that is often dumped into landfills. Sabotage, theft and other crimes perpetrated against such critical infrastructures must be punished in accordance with

relevant laws. Governments (especially for developing nations) must lead by example in showing their seriousness in addressing the challenges of poor electricity infrastructure development that has obviously impacted all aspects of the existence of their citizens.

VI. Conclusion

Sustainable energy transition is one of the greatest challenges facing humanity in modern times and we must continue to strive to tackle this challenge head-on. Added to grid expansion, MG development has proven to be a strategic and fast way to increasing access to affordable and clean energy. This paper has presented a region-agnostic and robust framework for sustainability-oriented IMGs described by 9-'Rs' and underpinned by sustainable engineering design principles. Our findings reveal that for IMGs in developing nations, efforts must be made to avoid repeating the same errors that were made at the national grid level (of many nations) which include underinvestment, operating legacy systems without relevant updating (and thus incurring high technical and operational costs), sabotage, non-implementation of good policies, etc. For developed countries, MGs and other electricity infrastructure design and operations must critically consider reduction of (electrical) waste, the role of retrofits and be a people-centric system instead of been heavily tilted towards profit maximisation for investors (without corresponding positive transformative evidence expected of the transition to sustainable energy system) which translates to unaffordable electricity bills, increased energy poverty and thus, slowing the pace of achieving SDG 7.

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