

The nexus of grids, mini-grids and off-grid options for expanding electricity access

State of knowledge paper

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Abstract

The purpose of this knowledge paper is to present a review of literature on the nexus between grid and off-grid electrification options and the enabling conditions to support each option. Through a thorough review of available academic and practice-oriented literature, this paper provides a synthesis and interpretation of the grid and off-grid electrification debate for electricity access. The paper finds that techno-economic studies do not consider the grid and off-grid alternatives directly and the suggested least-cost off-grid technology combinations generally represent relatively expensive solutions. The recent least-cost electrification planning models have considered the technology choice using geospatial information, but the model outcomes differ significantly due to, for example, granularity of the data used, the technology options considered, input assumptions about demand, economic activities, technology costs, operating costs, discount rates, and project life. More granular spatial data and model capability to capture low voltage distribution infrastructure appear to suggest greater attractiveness of decentralised solutions, whereas more aggregated analysis appears to support grid extension. Similarly, grid extension appears to be the least-cost option for higher demand or for concentrated population clusters, whereas decentralised solutions are more economic in dispersed areas with low demand.

The experience of successful universal electrification suggests no single governance template, but a strong leadership and an enabling environment is an essential requirement. Universal electrification requires a system-wide approach involving planning, coordination, and regulation. An appropriate organisational set-up and a robust regulatory framework can support the process. A shift from a grid-centric focus to a more inclusive approach to promote alternative options is important. Mainstreaming decentralised solutions, particularly mini-grids, requires favourable and reliable national regulations, adequate incentives and subsidies, and reliable information on the long-term plans for national grid expansion. Successful projects also require careful balancing of project economics and financial issues. The risks of grid arrival and the possibility of stranded assets loom large unless mitigation measures are considered.

Different pathways for power system transformation exist to develop a sustainable system while achieving universal electrification, but our understanding is limited or lacking in several areas. The existing planning models have adopted a technocratic approach to planning and the desires of local stakeholders are poorly captured by such tools. The quality of the data and the ability of the models to capture wider societal issues as defined by the Sustainable Development Goals (SDGs) remain major constraints. The capacity to transform planning studies into implementable programmes and to deliver electrification programmes remains limited. Similarly, further work is required to support sustainable electrification systems that do not impose a high-cost burden on future generations. Work is required to develop a programmatic approach to delivery and a more affordable and fairer outcome for all.

Keywords: grid versus off-grid electrification; electrification planning; HOMER; Network Planner; OnSSET; REM; risks; regulatory framework; project economics; least-cost

1 Introduction

1.1 Background

Energy access is the golden thread that joins three sustainability dimensions—economic prosperity, social development and living within the environmental limits. However, with around 990 million people without access to electricity and around 2.7 billion lacking access to clean cooking energies in 2017 (The International Energy Agency (IEA), 2018),¹ lack of energy access acts as a major hindrance to global efforts towards sustainable development. The population without access to energy is mainly concentrated in sub-Saharan Africa and South Asia, and the rural population in general and those with low income in particular suffer the most. For example, only 36% of rural habitants in sub-Saharan Africa have access to electricity as against 85% in developing Asia. The night light map of 2016 shows the level of electrification in 2016 (Figure 1).

Figure 1: Night light map of the world in 2016



Source: NASA Earth (https://eoimages.gsfc.nasa.gov/images/imagerecords/90000/90008/earth_vir_2016_lrg.jpg)

Further, despite rapid urbanisation, close to 3.4 billion (or 45% of the global population) were living in rural areas in 2018, but the incidence of poverty is three times higher in rural areas than in urban areas, and agricultural workers are four times more likely to be poor than those engaged in other activities (World Bank, 2016). Out of 766 million people globally (about 11% of the population) who were living with an income of less than US \$1.9 per day in 2015, 80% were living in rural areas. Clearly, access to clean energy is a prerequisite for sustainable development, and realising universal energy access remains a global challenge.

Despite a recent focus on energy access with the launch of Sustainable Energy for All in 2012 and the inclusion of energy access as a global sustainable development target in the form of Goal 7.1 of the SDGs to be achieved by 2030, the progress of energy access delivery has been slow in comparison to population growth. For example, although more than a billion people have gained access to electricity since 2000 (IEA, 2017), the benefit has not reached sub-Saharan Africa, where the size of the non-electrified population has increased over the past 16 years (from 518 million in 2000 to 588 million in 2016) due to population

¹ The SDG 7 progress report put the figure at 840 million in 2017. This difference in numbers arises due to methodological differences used in IEA reports and the tracking of SDG7 progress (IEA, the International Renewable Energy Agency (IRENA), United Nations Sustainable Development (UNSD), the World Bank, and the World Health Organization (WHO), (2019)).

growth. The spatial distribution of the incremental access gain reveals that, out of about 87 million people gaining electricity access between 2012 and 2014, 81 million were in urban areas and only 6 million of the rural population gained access, which was overshadowed by rural population growth (IEA and the World Bank, 2017). Clearly, progress with rural electrification remains unsatisfactory, particularly in sub-Saharan Africa, and reaching the bottom billion requires special attention (Bhattacharyya, 2018).

Rapid progress is required to meet the SDG 7 target of universal energy access in the future, particularly in low-income countries, highly indebted countries, and fragile states. Efforts have to be stepped up to meet the targets by 2030 (World Bank, 2017), and a modal shift is required to scale up from the current pilot and demonstration projects to accelerated programme deployments. The accelerated delivery of energy access to reach billions of population within a limited time and subject to resource constraints remains a challenge. There is also an opportunity for energy access interventions to catalyse sustainable rural development through better linkages with productive and transformative changes which could reduce rural poverty, improve rural living, and ease pressure on urban areas. In addition, in a carbon-constrained world, a systemic, strategic approach will be required to achieve universal energy access. It is in this context that the debate over grid extension and off-grid electrification options gains importance.

This knowledge paper presents a review of literature to highlight the nexus between grid and off-grid electrification and issues related to electrification. The methodology is indicated in Section 2, while Section 3 presents a review of literature on-grid versus off-grid options. Section 4 presents a review of the enabling environment in terms of policy and governance issues, while Section 5 discusses project economics, finance, and risks. Finally, Section 6 discusses the next steps and possible areas for further research.

1.2 Aims and objectives

The primary aim of the State of Knowledge (SoK) paper is to highlight emerging trends and priority research questions covering the nexus of grid, mini-grid, and off-grid options for expanding and sustaining electricity access. Specifically, the objectives are to:

- develop a state-of-the-art review of literature to understand the nexus of grids, mini-grid, and off-grid systems to help decide the remit of the DFID-funded Applied Research Programme on Energy and Economic Growth (EEG) to cover smaller systems; and
- identify potential research questions that could be considered for the next phase of the EEG programme.

The main research questions the knowledge paper aims to answer are as follows:

- what does the literature tell about the role of grid and off-grid options for electrification of the non-electrified population?
- what is the enabling environment required for supporting different options? and
- what affects the economics of an electrification project, and what are the risks involved?

2 Methodology

This work involves:

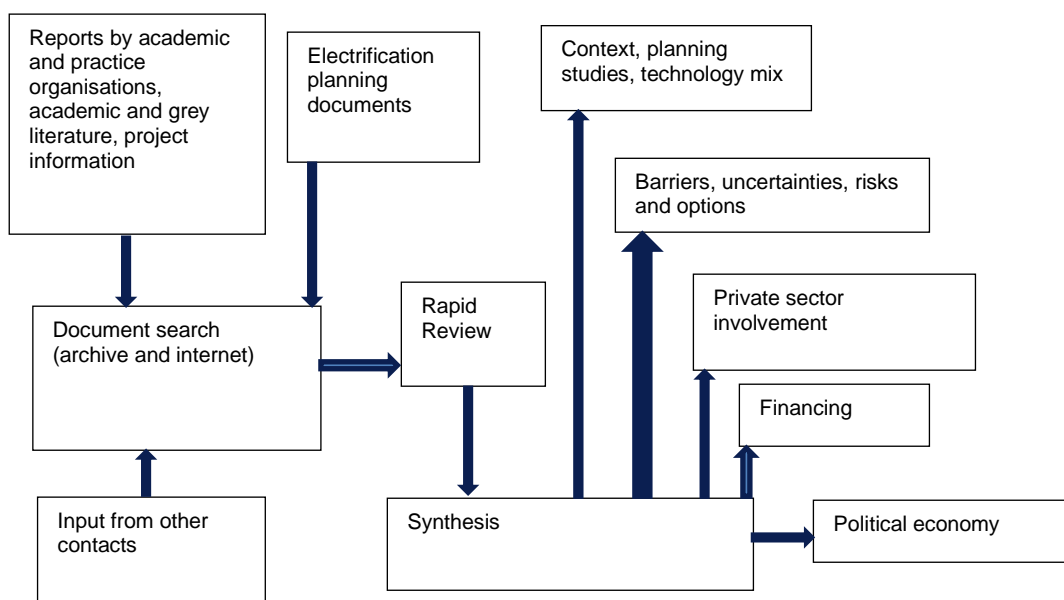
- contextualising the challenge of electricity access and the planning for rural electrification in the developing world, considering current national and international initiatives and relevant policies;
- reviewing the economic and financial imperatives and trade-offs, the policy and business environment, and the barriers, uncertainties, and risks to electricity access for both basic and productive use and rural electrification through alternative approaches;

- understanding the possible role and effectiveness of mini-grids in the above process; and
- identifying and investigating areas for further work.

A critical review of available literature was considered for this work. A rapid review of the available literature (academic and non-academic) was undertaken, and a selection of background reading materials was gathered using keyword searches on the internet and a search of document records in various databases.² Specifically, recent work on mini-grids and rural electrification undertaken by various international organisations (such as the Rocky Mountain Institute, IRENA, REN 21, the World Bank/Energy Sector Management Assistance Program (ESMAP), MIT, the Alliance for Rural Electrification (ARE)) were also extensively reviewed. Team members also collected information through personal contacts with other organisations.

The literature thus gathered was reviewed to identify contextual information, barriers, risks and options, private sector involvement, financing, and political economy. A synthesis of the reviewed documents forms the basis of information for the study. The review process is presented in Figure 2. The authors relied on critical thinking and analysis of the available knowledge to develop the main arguments of this paper.

Figure 2: Schematic of the literature review process



Source: Authors

3 Literature review on-grid versus off-grid options, trade-offs, and progress

The history of the electrification of the developing world started in the colonial period in the late 19th and early 20th centuries. Hasenöhl (2018) argues that the modern infrastructure development in the colonial era was a disjointed effort that benefited only a certain section of the population, often based on ethnic and class lines and thereby excluding the vast majority from the benefits of these services. At the time of

² The databases queried to search for appropriate studies include JSTOR, Google Scholar, Science Direct, Springer Link, UNDP, and the World Bank. Each of the databases was queried with search strings comprising of individual phrases and various combinations of terms, such as 'rural electricity', 'rural electrification', 'electricity access', 'grid electrification', 'off-grid', 'decentralised electricity system', 'distributed generation', 'decentralised renewable energies', 'solar PV', 'solar mini-grid', and 'techno-economics'.

gaining independence between the 1940s and 1960, grid electricity access in most British colonies was limited to few urban dwellers and a small proportion of rural inhabitants (Hasenöhr, 2018).

The academic and practice-oriented literature on rural electrification is well developed. Bhattacharyya (2012) categorises the literature according to three strands: the literature on technical systems and their cost effectiveness, using mainly a case study approach; the literature on tools and their applications; and the practice-oriented literature. Panos *et al.* (2016) identify four strands in the literature: case-oriented studies that describe the present situation in a country or region and evaluate policies and programmes; technological solution-oriented studies that focus on solar photovoltaic (PV) and other renewable energies and decentralised systems such as solar home systems or micro/mini-grids; national/regional studies linking energy poverty with economic development, either qualitatively or quantitatively; and model-based studies that try to combine economic, technical, and policy dimensions to analyse their complex interactions. Mandelli *et al.* (2016) on the other hand reviewed more than 350 papers on the subject and classify them into five research areas: technology; models and methods; techno-economic feasibility; case studies; and policy analysis. Yet another study carried out an extensive review of the literature to analyse the role of grid and off-grid options in facilitating rural electrification by undertaking a comparative assessment of their costs and impacts on the South Asian countries (Palit and Bandyopadhyay, 2016).

Rojas-Zerpa and Yusta (2014) find that the studies on rural electrification with decentralised energy sources started in the 1980s, but that most of the studies appeared in the new millennium. They also find that earlier studies used linear programming as the solution technique, but recent studies have used a wide range of techniques, with multi-criteria decision making playing an important role. They also observe that most of the studies deal with a short- to medium-term planning horizon and that long-term planning has received limited attention. The vast majority of the literature has taken a project-level analysis of techno-economic feasibility for a given location. These case studies have generally followed a common approach—assessment of technological appropriateness in a given context, evaluation of economic viability, and determination of financial or other incentives required to make the project viable at a given location (Kaundinya *et al.*, 2009). Most of these studies consider the off-grid option explicitly and the possibility of grid extension is considered through cost comparison, without overtly considering the grid extension possibility. Optimisation has played an important role in electricity planning studies, and the least-cost option for rural electrification has often relied on such an optimisation process. Although some studies have relied on their own formulation of the optimisation problem (e.g. Sinha and Kandpal, 1991; Kanase-Patil *et al.*, 2009), the proliferation of case studies can be attributed to the availability of standard software packages such as HOMER (Hybrid Optimisation of Multiple Energy Resources). These packages allow users to identify the optimal system configuration that would meet the demand at the least cost. These simulation tools offer a range of technology options, allow different performance characteristics, and capture local resource information. The recent version of HOMER Pro allows the possibility of specifying the reliability of grid supply in the modelling exercise.

Although energy access was identified as a major issue in 2002, it took almost 10 years to mobilise global attention. In 2011, the IEA came up with estimates for achieving universal electricity access by 2030 suggesting that grid extension is the cost effective option for urban areas and 30% of the rural areas which electricity has not reached. However, decentralised solutions are better choices for 70% of the rural population, where mini-grids and standalone solutions are likely to have a 65:35 market share (IEA, 2011). This figure (70% of new electricity access via decentralised solutions) has dominated the discussion for a decade now. The recent outlook has revised the share of decentralised solutions to 50% (IEA, 2019), but based on progress so far and the intensity of the efforts required to scale up and replicate decentralised solutions widely, this estimate has to be used with caution.

3.1 Review of HOMER studies

HOMER is the global standard for modelling electricity access that allows selection, sizing, and comparison of generation technologies and storage to meet demand in a given location, either using a standalone system or a mini-grid. The least-cost solution to meet the demand is obtained by running a large number of simulations of alternative combinations of options considering the local resources, system constraints and project specific conditions (life, prices, etc.). Hundreds of studies have been reported in the literature to suggest the least-cost technical solution for local electricity supply. Considering its popularity, relevant information from a selected set of recent HOMER applications from different countries is presented in Table A1.

A few observations can be made here.

- The analysis reported in these studies represents the techno-economic feasibility of project ideas and is not about real projects existing on the ground. There is a dearth of studies revisiting the optimal technical choice of real projects using HOMER. Exceptions include Chmiel and Bhattacharyya (2015), who investigated the off-grid system on the Isle of Eigg, Scotland; and Singh and Balachandra (2019), who reported a study of a PV-Biomass gasifier project being implemented in a remote Indian village.
- The hybrid off-grid systems simulated through HOMER have considered a combination of technologies, but most do not consider the grid extension option explicitly. The cost comparison of the optimised solution with grid supply is used to demonstrate the effectiveness of the off-grid solution.
- There is significant variation in terms of electricity load considered: some have focused on household load only, whereas others have considered commercial and institutional and even agricultural demand. The simulations do not limit themselves to basic levels of services (i.e. basic lighting and mobile charging) in most cases (see Table A1 for some examples), and include various combinations of end-use appliances considered relevant in the case study area.
- Most of the studies have reported results in US dollars, but a few cases have reported the results in local currencies. The technology cost is often sourced from international references and either local market conditions are not well reflected or data from actual projects were not used.
- There is significant variation in terms of discount rate choice. This becomes even more important when the investment is considered in US dollars, but the discount rate may not have truly reflected the cost of capital.
- The cost of electricity supply reported in most cases remains generally high, varying between US \$0.207/kWh to US \$0.5/kWh (see Table A1). Although the chosen option is the least-cost option among other alternatives, the results confirm the relatively high cost of off-grid electricity supply.
- The net present cost also remains significant, ranging from US \$68,500 to US \$17.5 million. The studies report simulation results but do not consider how the investment could be funded.
- There is hardly any direct comparison with grid extension. Where this option is considered, the grid is found to be expensive in two cases but cheaper in one case. Comparison using the same indicators or normative basis is also absent. In many cases, the best figure for off-grid is compared with poor figures for grid and *vice versa* to show that one is better than the other.

Cader *et al.* (2016) highlight the main limitation of HOMER as a tool: the model does not include any geospatial planning element, and accordingly it does not suggest how the consumer clusters are connected to the grid or the alternative technological solutions. Consequently, HOMER is not suitable as a planning tool.

3.2 Review of studies using planning models

New modelling tools have emerged in recent times that use spatial data at the local, national, and regional levels. Ciller *et al.* (2019) and Korkovelos *et al.* (2019) review the relevant literature. Local-level studies include Quinonez-Varela *et al.*, (2007) who explore grid integration of renewable energies in Scotland; and Sahai (2013), who presents an example of planning for Indonesia highlighting the case of an island. Sahai (2013) suggests grid extension for 66% of the population of the island, followed by mini-grids for 33% and standalone solutions for 1%. National-level studies include Castalia Strategic Advisors (2009) and Deloitte (2018). Castalia Strategic Advisors (2013) use a spreadsheet model linked with a Geographical Information System (GIS)-based database to analyse the technology choice for electricity access in Rwanda. The study found that grid extension is the least-cost option for 95% of the population, off-grid micro-hydro systems are suitable for 4.5% of population, and the remaining population can be provided with standalone systems. Deloitte (2018) analyses the electrification plan for Zambia using open source software developed by USAID's Southern Africa Energy Program. The study suggests that if all households are electrified by 2022, then solar home systems (SHS) would account for 75% of the population and 25% would be provided by grid extension. In the 2030 horizon, the technology mix changes somewhat: grid extension will support 34% of the population; SHS will reach 58% to 68% of the population and mini-grids will reach 1% to 8% of the population.

Moner-Girona *et al.* (2016) and Moner-Girona *et al.* (2017) report the case of the universal electrification of Burkina Faso. It suggests that, out of 10.8 million people in non-electrified areas, grid extension is the least-cost option for 4.4 million, whereas decentralised solutions are cost effective for the remaining population. In already electrified settlements, grid extension is a cheaper option to provide electricity to those lacking access (3.9 million) but PV systems will be the cheaper option for 0.8 million people, mostly in rural areas. Moner-Girona *et al.* (2019) analyse the case of Kenya and compare model outcomes with the electrification master plan prepared by the national electricity company. While the master plan aims at extension of diesel generation for non-grid areas, the model simulations suggests that PV-based mini-grids could be cost effective in most off-grid areas. One of the differences in the outcomes is due to the cost assumption used in two studies: the master plan assumed €3.5/Wp for PV, whereas Moner-Girona *et al.* (2019) use € 1/Wp. A report on the cost of solar PV in Africa, however—IRENA (2016b)—indicates much higher solar PV costs for mini-grids: systems without batteries vary between US \$2.5 and US \$2.9/W, and costs rise significantly for battery-inclusive systems (US \$2.5 to US \$10.9/W).

At the regional level, Szabo *et al.* (2011) presented an analysis of electrification options for sub-Saharan Africa. The analysis considers standalone solar PV, diesel mini-grids, and grid extension options. The study finds that grid extension becomes a viable option for locations with a high number of consumers and that it is not cost effective for sparsely population areas. PV becomes the most attractive technology for levelised costs between c€0.25 and c€0.3 per kWh. However, the study also suggests that, over large regions, neither diesel generators nor PV offers affordable electrification solutions (prices lower than US \$0.3/kWh are considered as affordable). In a subsequent study, Szabo *et al.* (2013) introduce mini-hydro as an additional technology (along with off-grid PV and diesel generators) and compare its cost effectiveness with grid extension. They suggest that removing diesel subsidy will reduce the importance of diesel generation in the continent. Grid extension is not the only option for enhancing electricity access; a combination of different portfolios of local renewable energy solutions will ensure a long-term sustainable outcome. Huld *et al.* (2017) present a tool for analysing the performance of solar PV mini-grids over large geographical areas (Africa and Southeast Asia). The study combines geospatial analysis with mini-grid performance optimisation at the continent level. The study suggests that, in desert areas, mini-grids are unlikely to experience energy shortage to meet the demand, whereas in other areas the interruption can be significant. For example, in India, mini-grids can face energy shortage for 20%–25% of the days, whereas in parts of China the interruptions can affect more than 80% of the days. This highlights the importance of local conditions for mini-grid system design.

Box 1 provides a brief review of the development in spatial electrification planning models. We focus on the application of three tools—the Network Planner, the Open Source Spatial Electrification Toolkit (OnSSET), and the Reference Electrification Model (REM)—because of their influence on the grid-off-grid electrification debate. It should be mentioned that this choice excludes any commercially available tool, as well as several other tools such as those developed at the Joint Research Centre (JRC) or by individual researcher groups, such as Reiner Lemoine Institut, but some applications of these tools (e.g. Szabo *et al.*, 2011, 2013; Moner-Girona *et al.*, 2019; Moner-Girona *et al.*, 2016; Ceder *et al.*, 2016; etc.) have been captured in the paper at relevant places.

Box 1: Evolution of GIS-based electrification planning models

Efforts towards developing decision support systems for the integration and analysis of renewable energies using GIS started in the 1990s. The SOLARGIS project was the main effort in the area of electrification of dispersed areas using renewable energies. Monteiro *et al.* (1998) reported an application of the methodology in Cape Verde. Other applications of this tool were reported in Amador and Dominguez (2005), Dominguez and Amador (2007), Pinedo *et al.* (2007), Dominguez *et al.* (2008), and others. Subsequent efforts led to the development of the IntiGis model, but the interface of this tool was in Spanish. The Economic Community of West African States Centre for Renewable Energy and Energy Efficiency redeveloped the model as IntiGIS2 for adoption in West Africa with a more user-friendly interface. This has more recently evolved into the ECOWREX model.

IMPROVES-RE was one of the earlier efforts in geospatial analysis used to support electrification efforts of Burkina Faso. GEOSIM, a proprietary model used commercially by IED (Innovation Energie Développement), was developed from IMPROVES-RE. GEOSIM has been used for the electrification planning of Tanzania (reported by Korkovelos *et al.*, 2019). Cader *et al.* (2016), however, suggest that, although it is an advanced tool, GEOSIM lacks one capability: it cannot model solar PV-based hybrid mini-grids. LAPER (*Logiciel d'Aide à la Planification d'Electrification Rurale*) is a model developed by Electricity de France and ADEME (Fronius and Gratton, 2001) for grid and off-grid choices using GIS data. The model appears to have capabilities similar to more recent models but it has not been used widely. Soler *et al.* (2003) reported an application of this model in Morocco.

The open source framework of electrification planning was initiated through the Network Planner model developed by the Modi Research Group. The JRC of the European Union developed a tool (RE2nAF) to explore the off-grid electrification options in Africa and Asia. The tool has been developed linking PVGIS with a number of models to analyse different renewable energy options and compare the outcomes with grid extension. OnSSET represents the next generation in the GIS-based analysis and has received wider support from international organisations. Another tool, REM, has also been reported in the literature which combines planning as well as network design capabilities. However, both OnSETT and REM models are not web-based yet and are not easily accessible to non-expert users.

Source: Korkovelos *et al.* (2019); Moner-Girona *et al.* (2018)

The Network Planner, a web-based tool developed by the Modi Research Group at Columbia University, has been widely used to explore the grid versus off-grid choice. The model compares grid extension with diesel mini-grids and standalone PV systems. The model allows different demand categories, and most of the studies have considered residential demand, productive load, and institutional/community loads. In some cases, demand by income categories has also been considered (see Table A2). Its ease of use has facilitated a number of applications in developing countries such as Nigeria, Ghana, and Kenya (see Table A2 for additional details).

One of the main observations from Table A2 is the predominance of grid extension as the outcome. In most cases, grid extension has been suggested as the least-cost option. The other observation is the relatively high cost of electricity supply in most cases, although grid supply comes out cheaper. It needs to be mentioned that, for grid supply, the model considers only the cost of network infrastructure development and does not consider the cost of incremental generation. It is assumed that the energy is available from the grid and no additional generation capacity is required to meet electrification needs. This assumption may not hold in many cases. The network maintenance cost is usually taken as a fixed value of the investment cost and this may underestimate the cost of grid supply.

The Network Planner model can deal with large volumes of spatial data, but the technology choice is limited and the solar mini-grid option is not considered. The mini-grid option considers diesel mini-grids only and this limited technology choice option has influenced the results. As the running cost of diesel generators is high, the mini-grid option proves less favourable to grid extension. The falling prices of solar panels and the modular design of solar PV mini-grids were not considered in these studies, which limits their usefulness. In addition, the data availability may also have affected the results to a certain extent, and most of the reported studies have used aggregated data. For example, Ohiare (2015) uses data at the local government level, not at the village level. As the demand is aggregated over a larger area, the electricity demand at the local government level is much higher than that at the village level. High demand at each node makes grid extension a viable option compared to other alternatives. More granular data are likely to lead to a different outcome. In addition, the studies could not take advantage of cost reduction in solar PV-based mini-grids, which has limited the possibility of lowering the cost of supply. Salam and Phimister (2016) argue further that the effectiveness of the heuristic algorithm used in Network Planner deteriorates as the dispersion increases and the remoteness of the settlements increases from the grid network. This creates a systematic bias towards grid extension in the model.

The OnSSET model has been applied to a number of developing countries (see Table A3). The energy access outlook of the IEA has relied on this modelling. Unlike the Network Planner, OnSSET offers a larger set of technology choice and uses a much bigger dataset in general. Although it follows closely the underlying analytical logic of the Network Planner, the data and technology options produce different outcomes. Table A3 reports a sample of applications of the modelling tool using the similar set of information provided for HOMER and the Network Planner.

A few observations can be drawn from Table A3.

- Earlier studies (2015–2016) reported a large potential for grid extension, while more recent studies offer a nuanced outcome. The scenarios used in recent studies suggest that as demand grows from the lower tier to the higher tiers, the viability of grid extension improves, and only in the high demand cases, the grid extension option dominates. At lower levels of demand, a characteristic of remote habitations, off-grid solutions play an important role. The Malawi study (Korkovelos *et al.*, 2019) for example assumes a basic level of rural demand, which makes standalone systems more suitable for these locations.
- The role of mini-grids does not appear to be significant in any of the cases shown in Table A3. Instead, the standalone PV technology appears to receive preference for low demand scenarios. This outcome is quite different from other studies, which report low penetration of standalone PVs. This outcome may be influenced by the existing and planned infrastructure investment in the electricity sector, which is captured by the OnSSET model.
- Country context plays a significant role in the choice of technology—larger, densely populated areas support grid extension, whereas standalone solutions are more cost effective for low demand, sparsely populated areas.

REM is a more recent development. Ellman (2015) presents the initial model through a local application in India (planning for a district in Bihar). Amatya *et al.* (2018) explain that the model performs least-cost electrification design by identifying the optimal technology option at a high level of spatial granularity. Ellman (2015) describes the logic used in the model, data requirement, and calculation principles. Like the Network Planner and OnSSET, REM identifies grid-off-grid choices, but it also designs the micro-grid system and the local network. Drouin (2018) argues that, in terms of user-friendliness, the Network Planner is better than OnSSET or REM, but REM and OnSSET have better technology choice capabilities. REM has a higher level of granularity in the sense that it can consider household-level demand and can design the network down to the individual consumer level.

The model has been applied to different cases—local, regional, and country levels. Table A4 provides some examples. The Vaishali district electrification example given in Ellman (2015) appears to have been the first application of the model at a local level. Similar local examples are provided in Mwalengi *et al.* (2016) and Gonzales-Garcia *et al.* (2016). REG (2019) is an example of country-level application of the model. One difference between this and the other models is that most of the publications are not peer reviewed and a majority of them are student research activities and consulting works. Although the model appears very comprehensive, it has not yet been very popular in terms of application.

Yet, REM applications appear to be suggesting different outcomes compared to other models. For example, Ellman (2015) finds that 85% of the population might be electrified via mini-grids, whereas isolated systems are more effective for the remaining 15% of the population. No grid extension is recommended in the base case scenario. Amatya *et al.* (2018) present a representative example with around 52,000 users in a locality of 65 km x 45 km area. Data from different sources are used for the case study to demonstrate the model with a large-scale example. The results show that 51% of the consumers could be provided with electricity through grid extension, 17% through a mini-grid, and 32% using standalone grids. As indicated in Table A4, most applications indicate a very high share of mini-grids. Grid extension does not emerge as the most appropriate solution in these applications. These results are very different from other studies. The demand characterisation, among other factors, is likely to have played an important role here. Most of the REM studies have considered many different types of loads, but the residential load considered in these studies is much lower than other studies.

Results obtained from the Network Planner, OnSSET, and REM for a given country can provide some insights. For Kenya, using Network Planner Parshall *et al.* (2009) suggest that, in the realistic grid penetration scenario, 41% of the households will be connected to the grid by 2030, but in the full penetration scenario this increases to 96% over the same period. Grid extension is the least-cost option in densely populated areas where the grid infrastructure is already available. In the sparsely populated areas, on the other hand, off-grid solutions are most cost effective. The grid-related investment required for the realistic scenario is close to US \$5.9 billion, whereas the investment requirement increases to US \$13.4 billion in the full grid penetration case. Using the OnSSET model, in contrast, Moksnes *et al.* (2017) suggest that, in the low demand scenario, only 53% of the population will be grid-connected by 2030 and 47% of the population will be electrified by standalone solutions. The investment requirement is estimated at US \$21.4 billion. Mwalengai *et al.* (2016) (using REM) suggests that 96% of households in Kilifi in Kenya could be connected via mini-grids. There is no national-level study using REM but, going by this case study, the emphasis on mini-grids can be easily identified.

Differences in the model results can arise due to a range of factors. A few areas are highlighted below.

- The studies considered in the previous paragraphs were undertaken at different times using different datasets. Parshall *et al.* (2009) relied on data available around 2007. Moksnes *et al.* (2017) relied on data from 2013 onwards. Mwalengai *et al.* (2016) used data from 2012. Different vintages of the studies make comparison difficult.
- As indicated earlier, the granularity of data plays a major role. More granular data appears to suggest greater cost effectiveness of alternative solutions. REM appears to use low voltage distribution network data into consideration whereas other models have limited the scope to medium voltage lines (11 kV). The bias for grid extension may be related to this lack of capability to use lower level system data.
- Load data is another critical variable. Most of the studies indicate that, as the demand increases from the lower tier to the higher tiers, grid extensions become a more preferred solution. The spatial distribution of demand, the assumptions related to population growth, demand growth, and inclusion/exclusion of non-household demands affect the model results. Studies that have considered higher levels of residential load appear to suggest higher levels of grid extension whereas those using basic level of demand for residential users appear to recommend a higher share of alternative solutions.

- Further, there is uncertainty in predicting consumer electricity consumption. The general reliability and accuracy of the surveys has not been demonstrated: based on a comparison of survey-predicted electrical energy use with the actual measured consumption of consumers of eight mini-grids in rural Kenya, Blodgett *et al.* (2017) question the reliability of surveys.
- Similarly, the assumptions used in the models vary: there is no consensus value for the investment cost of technologies, the running costs (fuel price, efficiency, transportation costs, labour cost, etc.), the cost of capital, or project life. No study has tried to use alternative models using uniform assumptions. Accordingly, the effect of model idiosyncrasies on the result is difficult to identify.

The studies reported in Tables A2–A4 are mostly academic in nature and only a limited number of them have informed actual rural electrification planning of countries concerned. Watcheung *et al.* (2010) report a significant gap between the state-of-the-art in the planning tools and the practice being followed by members of Club of African Agencies and Structures in Charge of Rural Electrification. Based on a detailed review of literature, Trotter *et al.* (2017) also find that most sub-Saharan African countries have received little attention regarding electricity planning and only a few countries receive most of the attention.

In addition to the above, we did not find any literature comparing model predictions against actual electrification in specific countries. Such a comparison could show whether the models are aligned with the real developments, and the reasons for any divergence between the two could offer insights into models and help improve our understanding. This could be an area of further research.

3.3 Review of electrification plans

A review of national electrification plans of 20 countries with the largest number of non-electrified households by Ma and Urpelainen (2018) shows that 14 countries have national plans for rural electrification and 12 countries have demonstrated a commitment to distributed power generation, but only 10 countries have made investment budget allocations and 12 have established a policy instrument to deal with decentralised electrification. Further, in most countries, decentralised electrification has been considered to supplement the areas where expansion of grid is daunting. This shows that distributed electrification is not considered a universal approach in the planning of electrification strategy (see Table 1).

Table 1: Emphasis on decentralised electrification option in national plans of selected countries

Country	Population lacking access (M)	National plan	Commitment	Investment budget	Policy instrument
India	269.51				
Nigeria	74.73				
Ethiopia	70.88				
DR Congo	63.77				
Bangladesh	59.94				
Tanzania	44.14				
Uganda	30.91				
Kenya	29.46				
Myanmar	24.92				
Mozambique	21.44				
Sudan	20.79				
Madagascar	19.62				
Angola	18.31				
DPR Korea	16.99				
Niger	16.41				
Malawi	15.04				
Burkina Faso	14.21				
Chad	12.48				
Mali	12.33				
South Sudan	11.01				

Source: Based on Ma and Urpelainen (2018)

The United Nations Conference on Trade and Development (UNCTAD) (2017) remarks that some countries such as Lao People's Democratic Republic (PDR) and Senegal have been successful in extending electricity access without a centralised national plan, but other countries may not be able to follow such a path. Realising this gap between practice and the state-of-the-art knowledge, Sustainable Energy for All has launched a call for a full-systems approach to electrification adopting a five stage process (Figure 3). While such a systemic approach is desirable, implementation remains a challenge, and it remains to be seen to what extent such a process is practically adopted by the concerned countries.

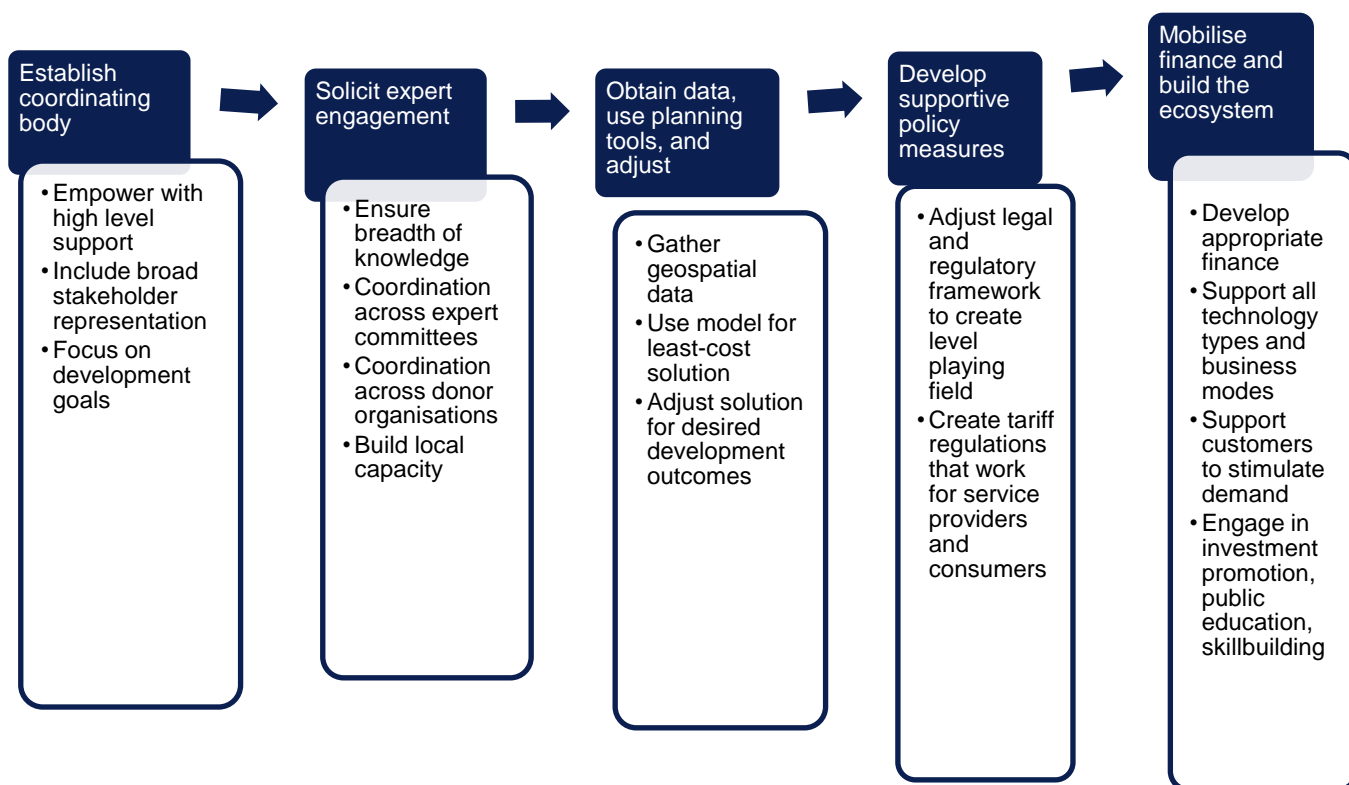
Our review leads to the following takeaways.

- Techno-centric focus:** the existing research has predominantly focused on technical dimensions of the problem, with a significant emphasis on electricity access for basic services. Attention is often limited to specific technologies or combinations of technologies for energy production, their cost effectiveness, and optimal technology mix of choices. In many cases, the studies have relied on assumed information or characteristics of user needs without any serious stakeholder engagement or long-term data from real field projects. The proliferation of hypothetical simulation cases is surprising. Further, while optimal technology choices by HOMER may consist of hybrid options with multiple technologies, in reality most projects are implemented either using single technologies and/or combination of only two technologies by the implementing agencies (government or private). So there appears to have a gap between actual implementation and modelling exercises. Why multiple technology based hybrids are not implemented in practice needs to be found out. Despite the proliferation of such studies, their

contribution to knowledge remains marginal as the practical usefulness of the research outcomes to solve local issues remains limited.

- **Inadequate attention to planning for accelerated growth:** while it is now recognised that progress so far has been slow and that a faster growth in energy access provision is required to meet the target of SDG 7.1 by 2030, hardly any attention has been given in the literature to the planning of such a large-scale programme. The planning studies reviewed here have limited their attention to identifying the technology mix and total investment needs. However, hardly any studies translate them into an implementable programme, although Shrestha and Acharya (2015) and Sustainable Energy for All (2019) provide relevant planning frameworks. Efforts need to move from local plans and pilot projects to country-level plans and mass rollout of programmes, for which programme-level synergies, standardisation, and appropriate planning processes need to be investigated. In addition, prioritisation of investment considering funding constraints, human resource scarcity, and administrative and other considerations has not been given attention so far. The lack of planned efforts may be due to funding constraints on implementing national-level programmes or to a lack of vision and adequate information in specific countries. Where a lack of vision/information constrains the planned progress, programmes such as Electricity and Economic Growth could support countries to develop holistic electrification programmes based on which the counties could solicit funds from donors and multilateral funding agencies.
- **Role of decentralised options:** although claims are often made that decentralised options are least-cost solutions for majority of the population lacking electricity access (e.g. the recent policy brief for the High Level Political Forum claims that decentralised solutions are least-cost options for 60% of population lacking electricity access (UN, 2018)), our review did not find any clear evidence to support such a claim. Apparently, simulations using HOMER offer the largest evidence base supporting the cost effectiveness of decentralised solutions; but, as indicated previously, these studies have not considered grid extension explicitly and most are assumed (and not real) case examples. The results of the planning studies are inconclusive, and most appear to suggest a mixed-bag approach where grid and off-grid solutions will play a role. Earlier studies using the Network Planner have suggested a higher role for grid extension, whereas more recent studies using OnSSET suggest some role for decentralised solutions. Moreover, decentralised solutions are usually considered beyond a threshold distance from the grid; but, as the grid expands, previously identified off-grid habitations cease to be the least-cost option due to shrinking distance. Planning models do not appear to capture this continuous revision to the plan.
- **Ex-post performance evaluation:** while interventions in energy access have sharply increased recently, there is limited empirical research to monitor their long-term performance and effectiveness of decentralised options. In most cases, hardly any information is available after the investment is made, and no systematic framework for evaluating the sustainability of such interventions yet exists. Project performance evaluations can provide important lessons for improving the effectiveness of interventions. There is an absence of a clear performance measurement metrics for mini-grid performance evaluation and monitoring. This remains an area for further research.

Figure 3: Process map for an Integrated Electrification Pathway



Source: Sustainable Energy for All (2019)

4 Review of the enabling environment for different electrification options

4.1 Fundamental principles for successful electrification

The previous section has shown that universal electricity access will rely on a combination of grid and off-grid solutions. A review of success stories of countries that have achieved near-universal electrification shows that there is no single template for success, and that all countries have used ‘home-grown’ models. Nevertheless, these cases suggest four fundamental principles for successful electrification programme design and implementation (ADB, 2016; World Bank, 2011):

- 1) visible and committed government leadership;
- 2) an enabling institutional environment;
- 3) sufficient and sustained financing; and
- 4) broad stakeholder engagement and coordination.

This section reviews the enabling environment, while Section 5 presents finance and other issues.

As a first step, a strong government commitment and leadership is essential for setting the electrification target and developing an electrification programme. Successful countries have pursued the electrification

policies over decades and such a long-term government commitment was a prime feature of success in China, Thailand, India, and Vietnam (World Bank, 2011). A clear vision about the future of the electricity system and an identified leadership to implement the vision is essential. The vision must indicate deliverable targets and appropriate benchmarks on the levels of access and quality of service (UNCTAD, 2017).

Next, an enabling governance structure is critical to define the ownership structures, duties, and responsibilities of different actors and the operation of the electricity sector (UNCTAD, 2017). The organisational structure, the rules of the game (policies, regulations, legal frameworks), and arrangements for coordination of the activities of different entities will vary depending on the electricity market structure. In addition, depending on the level of access and future electrification targets, the pathways for electricity system transformation will be different; but a system-wide approach involving planning, coordination, and regulation is required in each case to avoid a suboptimal transformation of the electricity system (UNCTAD, 2017). Chattopadhyay *et al.* (2014) argue that planning failure is a factor affecting the progress with 'electricity for all' campaigns and that a better coordination of the entire planning process covering generation, network planning, and distribution with the help better data is a prerequisite for success in energy access delivery. Strategic thinking about generation system expansion planning to scale up supply and diversify the generation mix, develop and upgrade the network for supply, and integrate with other regional markets where feasible is essential for the transformation of the electricity system of developing countries. System-wide planning holds the key here (UNCTAD, 2017).

From an organisational perspective, a national entity for overseeing the electrification programme and harmonising the efforts of different stakeholders is required. It is important for such an entity to have a clear responsibility, a transparent electrification process with minimal political interference, and a mandate to liaise with other governmental agencies and departments to ensure linkage of electrification with local development initiatives (World Bank, 2011).

The governance arrangement needs to provide a robust regulatory system that is clear, transparent, and independent of government interference. An effective regulatory arrangement will encourage participation of different actors in the sector, delimit the grid-off-grid jurisdiction, provide a tariff system that is fit for the given condition, and promote innovation in the system. It will also protect the consumers and make the suppliers accountable (World Bank, 2011). However, the regulatory capacity is a challenge in most developing countries.

4.2 Mainstreaming off-grid solutions

Mainstreaming off-grid and mini-grid solutions within the national electricity access plans is an important first step to provide a strong base for development of the sector. This also incentivises different stakeholders to work out tailored solutions to enhance energy access. Many countries have adopted a range of approaches and introduced targets to cover unserved and underserved communities using off-grid and mini-grid solutions to complement central grid connections. By 2016, out of the one billion individuals who had gained electricity access since 2000, about 133 million people were served by off-grid renewables, of whom about 2.1 million people were connected to solar mini-grids. While the overall share may be low, recently the growth has been enormous. Between 2008 and 2016, the number of people connected to mini-grids tripled to nearly 9 million across Asia and grew six-fold to 1.3 million across Africa (IRENA, 2018). Several successful examples of mini-grid-based supply have been reported in the literature from around the world: Schnitzer *et al.* (2014) provide several examples of successful micro-grids from India, Malaysia, and Haiti covering private, government, and non-profit sector interventions. Wiemann *et al.* (2015) provide examples of mini-grid projects from around the world: one is Sunlabob, which has successfully developed a hybrid mini-grid in Lao PDR combining micro-hydro, solar PV, and a diesel generator. A United Nations Industrial Development Organization study (Draeck and Cottasz, 2017) provides examples of successful mini-grids in six African countries (Chad, the Gambia, Guinea-Bissau, Cote-d'Ivoire, Tanzania, and Zambia)

and two Asian countries (India and Sri Lanka). Ulsrud *et al.* (2018) provide a detailed analysis of solar mini-grid projects in Senegal, especially against the context of the broader dynamics of national- and international-level factors, including emerging system innovation and socio-technical transitions to green technologies. Box 2 provides a brief overview of mini-grid operator models and interconnection issues.

One cardinal requirement for success, irrespective of the operating models, is an enabling policy and regulatory regime. However, as highlighted in the last section, not many countries have policy instruments or allocated budget for decentralised electricity systems (Ma and Urpelainen, 2018). Some of the policy and regulatory challenges highlighted in the literature are summarised in Table 2.

Box 2: Mini-grid models and interconnection issues

Four main mini-grid operator models were primarily deployed: utility operator models; private operator models; community-based models; and hybrid operator models (IRENA, 2018; Franz *et al.*, 2014; ARE, 2014). These models differ in terms of who owns the power generation and distribution assets, who operates and maintains the electric system, and in the relationships between operator and the consumers. Each model also has its own pros and cons. While tariffs can be cross-subsidised with ease in the case of utility models, they are prone to political interference, especially in case of state owned utilities. The private operator models have a high potential for scale-up, attracting investments, and mobilising the best technology, but they are dependent on a supportive enabling environment, especially related to policy certainty. Community-based models, on the other hand, are best to ensure local ownership and inclusiveness but are exposed to management risks and usually require grant for capital infrastructure. Hybrid operator models combine different aspects of the abovementioned models and present a good compromise and starting point for scaling up.

The coexistence of mini-grids and grids could take two forms: interconnection of the distributed generators or mini-grids with each other (wherever possible) or with the centralised distribution grid system. This can improve the reliability of supply by balancing the power surplus and deficiency in the networks through power exchange. This becomes very important for mini-grids in the context of aggressive grid expansion in India, as well as in some sub-Saharan countries. This is also relevant for countries with lower electrification rates but with high interest from private sector developers to expand electrification-using mini-grids (e.g. Myanmar and sub-Saharan African countries). Although grid compatibility of the distributed generation infrastructure is stipulated in many countries to avoid the issue of stranded mini-grid assets once a village is connected to the grid, small plants and poor rural infrastructure cast serious doubts on such compatibility in reality. It may be noted that power export to the distribution network from a large number of small-distributed generators or mini-grids, with varying capacity and fuel mix, may alter the flow of electricity and affect the stability of the network. Interconnecting multiple networks can lead to undesirable dynamic behaviours and instabilities due to interactions between interconnected weak networks and/or the connecting converters. The resilience of the network stipulates that the individual units and the overall interconnected system deal with intrinsic and extrinsic events such as short circuits, connecting and disconnecting of networks, load application and shedding, and the loss of communication links (Palit, 2019). The cardinal principle of grid interconnection of mini-grid system is that quality of supply to consumers should be maintained at all times and should not unacceptably affect the distribution network. Conversely, the grid systems should not damage the distributed generation equipment, and the generator should be able to operate and evacuate power to/from the grid as intended. The central regulatory issue here is development of appropriate standards that will allow for a cost effective interconnection solution without jeopardising the safety and reliability of the electric power systems.

A regulatory framework along with exit mechanism for the decentralised electricity system developers is also crucially required to ensure the integration of decentralised generation to the central grid, when the latter does arrive (wherever applicable), so that the incurred investments do not sink because of the potential risk of under-recovery or non-recovery. Policies and regulations are required to allow the mini-grid project developers to sell power to the grid when local demand does not suffice or consumers have shifted to grid electricity. A cost-reflective feed-in tariff is essential in such a case. In addition, policies should support a scenario where any private company or entrepreneur desires to set up a distributed generation plant and also take the electricity from the grid at bulk at a price lower than the rural retail tariff and serve the rural areas. Both the above will not only reduce investment risk for mini-grid developers, but will also contribute to grid stability. The exit strategy will work even better if bigger electric utilities take over successful smaller utilities to reduce transaction cost considerably. Similar to the information technology sector, the smaller entities may be good at taking risk and experiment with innovative technical and delivery models, whereas bigger entities can bring down the cost of delivery due to

economies of scale, scope, and spread. However, unless there is policy clarity in the sector, bigger utilities will not make substantial investments. The electricity regulators, which are the authorities to provide the licence to distribute electricity, should play a more proactive role in ensuring a closer coordination of the distribution utility and mini-grid service providers, setting up interconnection standards and (most importantly) in legally acknowledging the delivery provisions through distributed generation.

Table 2: Policy and regulatory challenges facing mini-grids

Issues	Description
Lack of rural electrification planning or strategy	Mini-grid development is substantially easier in the context of clear national rural electrification plans. Among other benefits, such plans lay out a clear approach to conducting rural electrification efforts; specify the role that mini-grids are expected to play; provide crucial data regarding non-electrified populations; provide transparent information on where and when extensions of the national grid are to be expected; and may even designate areas where mini-grid development is favoured. A clear rural electrification plan and strategy is a crucial part of creating a favourable environment for mini-grid developers and operators.
Political and legal uncertainty	Mini-grid developers and operators often function under an uncertain legal framework regarding their ability to establish projects and offer electrical services to consumers. In the absence of well-formed legal and regulatory rules and structures, mini-grid developers and operators face significant risks, including political, investment, construction completion, and operational risk. A clear policy and legal framework provides the rules under which a mini-grid developer and operator must function. With greater clarity on the rules of the game, these entities can make informed project development and operational decisions.
Unclear or complicated regulatory processes and approvals	An unclear, lengthy, or costly approval process can end up imposing new or additional financial risks on already fragile mini-grid projects and may limit developers' interest in entering a specific market. It is thus critical for regulators to develop a straightforward and efficient approval process for mini-grid projects that can reduce project development costs and risks.
Lack of retail regulations	Mini-grid developer and operator decisions often depend on the level of payment expected from consumers. Without regulated tariffs, developers face significant uncertainty regarding the economic viability of their business model. Additionally, without clear retail regulations, mini-grid consumers may be more vulnerable to price gouging. Setting retail regulations can provide greater certainty and security to mini-grid developers, operators, and consumers.
Lack of technical standards and quality assurance	Without technical standards, decisions are left to mini-grid developers and operators. Even with good intentions, the decisions of developers and operators may lead to electrical safety issues, suboptimal quality of service, technical standards that do not align with national grid extension goals, or connection and service costs that are prohibitively high for many potential consumers. Technical failures, often due to inadequate maintenance and a lack of quality of components, are common for many mini-grids in sub-Saharan Africa. Flawed technical and safety standards and the resulting technology failures decrease trust on the side of the consumers. Laying out transparent regulations on technical standards and quality assurance can improve the quality, consistency, and reliability of mini-grid projects for developers, operators, and consumers.

Source: NARUC (2017); Manetsgruber et al. (2015)

An enabling policy and regulatory framework, together with other aspects (such as social, technical, and economic factors), is required to promote sustainable mini-grids. Examples of policies that have assisted growth of renewable electricity sector are feed-in-tariffs, differential tariffs, net metering, and tax credits/incentives. The key factors in the off-grid/mini-grid sector to consider include legal and licensing provisions, tariff regulations, financial support, quality standards, and eventual grid interconnection on arrival of the main grid. Furthermore, the lack of a clear policy environment increases the uncertainty and deters private investments (IRENA, 2018). The long-term viability of mini-grid concerns is also highly dependent on the arrival of national grid in a given area. Since consumers tend to prefer to be serviced by the central electricity grid due to the lower regulated price of electricity and the higher availability of load (Graber *et al.*, 2017), the possibility of mini-grids becoming stranded assets on arrival of the central grid is high.

The current state of mini-grid regulation varies significantly across countries. While mini-grids are a relatively new concept for many countries, as mentioned above, some have effectively deployed hundreds of mini-grids at the national level (e.g. Bangladesh, India, Tanzania, Cambodia, and Nepal, among others). In general, however, regulatory authorities have struggled to address the multi-stakeholder needs of an expanding mini-grid sector. Underdeveloped policy and regulatory structures are a high priority challenge facing mini-grid developers, consumers, utilities, and other stakeholders. In many instances, governments have not taken clear steps to define regulatory authority over mini-grids (e.g. India) or to set clear regulations for mini-grid deployment. Regulations developed for large national (and often government-owned) or private utilities are often inappropriate or not suited for small mini-grid developers. The structure of the regulatory authority overseeing the sector has often led to lax regulation, resulting in inconsistency and confusion regarding how mini-grid projects could be regulated (IRENA, 2018).

The World Bank's Regulatory Indicators for Sustainability (RISE) 2018 report shows significant improvement in sustainable energy policies globally, and the number of countries with advanced policy frameworks for sustainable energy has more than tripled over the past eight years (ESMAP, 2018). In countries with an access deficit, policymakers are increasingly turning their attention to off-grid/mini-grid solutions to close the energy access gap. This is illustrated by the share of low-access countries adopting measures to support mini-grids and solar home systems increasing from around 15% in 2010 to 70% in 2017. Interestingly, the same report indicates that, over the same timeframe, the enabling environment for grid electrification has remained relatively stagnant and now scores lower than for off-grid solutions. Despite the improvement in the policy sphere, the RISE report also highlights that the world is only about half way towards the adoption of advanced policy frameworks for sustainable energy and this puts at risk the achievement of SDG7 by 2030. Further, policy enforcement appears to be a key challenge. While strong policy frameworks are critical, they must be backed by effective institutions and enforcement. Among all the regions, sub-Saharan Africa has the weakest regulatory environment, with half of the countries deemed to have an underdeveloped policy framework (ESMAP, 2018). However, some countries within the region, such as Ethiopia, Rwanda, Tanzania, and Uganda, show a green rating for their policy environment.

To capture the developments and inform policymaking, IRENA launched its *Policies and Regulations for Private Sector Mini-Grids* report in 2016 with the objective of analysing the design elements of dedicated mini-grid policies being introduced by countries in developing Asia, sub-Saharan Africa, and Latin America (IRENA, 2018). The study was revised in 2018 by examining four key conditions for the development of private sector mini-grids—licensing and legal provision, tariff regulation and cost recovery, arrival of the main grid, and access to finance—through an analysis of several country case studies to gather insights on design elements of policy and regulatory measures for mini-grids and their application to the sector. The IRENA study classified the measures under primary (related to national energy framework), secondary (related to tax, land rights, environment, etc.), and tertiary (broader areas such as data, fossil fuel pricing, etc.) .

The IRENA analysis found that, in all the studied cases, a variety of measures have been taken to support mini-grids. While all studied countries have introduced at least some form of primary measures, the tally reduces for secondary and tertiary measures. Countries such as Rwanda, Nigeria, Peru, and Tanzania have all incorporated mini-grid solutions into their energy plans and strategies to provide the basis for the expansion of electricity services. Rwanda's National Electrification Plan (2018–2024), for instance, clearly demarcates areas for on and off-grid expansion and aims to mitigate the risk of uncertainty around grid expansion with the implementation of their electrification plan (Ministry of Infrastructure, Rwanda, 2018). Peru's rural electrification master plan is updated every two years to reflect conditions in the country and accordingly adapt targets and plans. Nigeria's mini-grid regulation, launched in 2017, has tried to consider the benefits from the lessons learned by other countries in the region, and was developed with extensive stakeholder engagement. It includes key provisions for tariff determination/regulation and compensation mechanisms in case of main grid connection, among other aspects. Similarly, Tanzania's Small Power Producers framework, which has evolved since 2008, aims to attract private sector participation in the development of both isolated and grid-connected mini-grids (Tenenbaum *et al.*, 2014). The first generation of the plan has taken lessons from the Thailand Small Power Producer Programme. The third generation of the framework is currently in force and provides tailored licensing requirements and tariff regulations depending on capacity. Tanzania's experience has also shown the importance of looking at secondary and tertiary measures to improve conditions for mini-grid development. It facilitates investment by simplifying the environmental regulatory requirements for mini-grid development, and provides a single-window clearance facility and a dedicated portal for all information pertaining to mini-grid policies and regulations.

The same study also observes that, while in a number of cases (including India and Cambodia) mini-grids have been deployed in a substantial number of different capacities in a largely deregulated environment, there are countries where they have been implemented in line with the policies formulated. For example, policies in Nigeria, Rwanda, Sierra Leone, and Tanzania have defined capacity thresholds for mini-grids (e.g. smaller than 100 kWp) that are either exempt from licences or follow a simplified processes (e.g. registration only). These countries also have the facility to secure a provisional licence providing 'temporary exclusivity' to developers for a specific period to develop the mini-grid project (Tenenbaum *et al.*, 2014). The licensing processes have also been standardised by several countries, such as Nigeria and Tanzania, which provide templates for documents (e.g. applications for permits or licences; exclusivity agreements; tripartite contracts).

In terms of standards and technical regulations seeking to ensure the safe and reliable operation of a system, an IRENA study³ indicates that quality infrastructure for mini-grids technologies is still at an early stage and is missing for the overall mini-grid system. Some countries, however, have attempted to develop standards for mini-grids. For instance, in Nigeria, to be eligible for a permit, mini-grids have to comply with the Nigerian Energy Regulation Commission's Distribution Code for the Nigeria Electricity Distribution System. The commission also offers recommendations for all mini-grid operators, whether they have a licence or not. Similarly, the Tanzania Bureau of Standards worked together with their regulatory body and international partners to establish a quality standard for mini-grids. In the case of Indonesia, the components do not only have to meet national/international standards; they also have to be locally manufactured. The International Finance Corporation established the Lighting Global Quality Assurance framework about a decade ago to evolve the standard and promote the adoption of off-grid solar products to enable innovation and support the market's development.

Apart from the above, adequate end-of-life management of mini-grids still poses a significant challenge to the environmental sustainability of mini-grids. Mini-grids powered by renewable energy are considered a climate-neutral technology. However, the production and disposal of the relevant equipment—from cables to switchboards to solar panels—has ecological footprints. Mini-grid equipment may fail (for example due to a lack of proper maintenance) and is often improperly disposed of, posing adverse health risks and the

³https://ioec.irena.org/-/media/Files/IRENA/IOEC/2018/Presentations-side-events/IOEC2018_SE6_Developing-quality-infrastructure-for-renewable-mini-grids_Salgado.pdf?la=en&hash=142BAB60021B34157506ECCE43213EBC127C2A9D.

emission of environmentally harmful substances (Manhart *et al.*, 2018). Proper end-of-life management is critical for the sustainability of mini-grid solutions but is not well researched.

In summary, to achieve universal access to electricity by 2030, reports suggest 40% to 50% of all installed capacity will have to come from mini-grids (IEA, 2019; World Bank, 2019). The World Bank (2019) suggests that the cost per kWh of mini-grid electricity is expected to decrease by two-thirds by 2030 and that 490 million people could be connected through mini-grids by 2030, for which 210,000 mini-grids need to be developed at an investment of almost US \$220 billion. To achieve this, a favourable governance arrangement and regulatory environment is required to provide a level playing field to alternative technical options, attract investors into the sector, and facilitate implementation of programmes. Mini-grids need favourable and reliable national regulations, adequate incentives and subsidies, and reliable information on the long-term plans for national grid expansion. Further enablers for the successful implementation of mini-grid projects are the thorough consideration of the specific needs and aspirations of the affected communities and reliable information about their actual and future electricity demand. Finally, mini-grids also need agreed technical standards and certification mechanisms to ensure safety and quality.

4.3 Towards the grid and mini-grid convergence

The literature review in Section 3 clearly brings out the fact that a mix of approaches will be needed to achieve universal electricity access. In similar vein, Palit (2019) opines that, instead of a binary perspective of centralised technology and centralised services or decentralised technology and decentralised services, what might be more prudent is a combination or a complementary convergence of centralised and decentralised energy technologies and delivery models, learning from each other's strengths both technically and institutionally. For instance, while a central grid is usually found to provide adequate electricity supply for meeting different types of loads (such as domestic, productive, and agriculture), and also have standard operational practices for delivery of infrastructure, electricity supply, and maintenance (such as protocols for transformer and distribution network maintenance), most mini-grids do provide efficient delivery of services but are constrained by their capacity to meet all types of load. The central grid could thus adopt a decentralised distributed model to improve their quality of customer service delivery, while mini-grid capacity could be designed to meet all type of loads either on standalone basis or in interconnected mode. Further, mini-grids should also develop standard operating practices for delivery of infrastructure and maintenance to reduce transaction cost. However, further context-specific research will be required to address the socioeconomic, regulatory, and technical challenges of interconnection of mini-grids and/or with the central grid and running a resilient and reliable local power network across different geographies.

Capacity building and local socioeconomic contexts may also drive the local actors and institutions responsible for operating the network. An enabling policy framework would therefore be equally important, as these actors and institutions have a stronger influence on the performance of the sub-national actors and institutions (especially in terms of decision making and effective monitoring) for effective infrastructure and adequate service delivery (Palit, 2019). An independent regulatory mechanism would enable the sharing of best service delivery practices, more objective tariff setting, and monitoring of the performance of the grid and mini-grid-based service providers, according to objective indicators. Furthermore, the involvement of consumers must be ensured in the regulatory process and should extend beyond well-informed and large consumers to include the relatively ill-informed small groups. Developing and embedding locally relevant frameworks and practices would require further work.

5 Project economics, finance, and risks affecting electrification

An enabling environment alone is not sufficient to ensure universal electrification. Issues related to project economics, finance, and risk management play an important role. This section deals with these issues. The focus here is on decentralised solutions.

5.1 Project economics

An off-grid electricity supply can take two forms—individual product-based solutions and community or collective network-based solutions (Bhattacharyya, 2013; Palit and Bandyopadhyay, 2015). The individual solutions usually involve sale of a product, similar to a consumer durable item, which enables individual households to produce electrical energy to meet basic household needs such as lighting or providing energy for charging a mobile phone or running simple electrical appliances such as a television, fan, etc. The community or collective solutions serve a cluster of households or an entire village, and provide electricity generally by generating from a diverse range of small local generators (such as solar PV, micro/mini hydropower, biomass-based technologies, etc.), with or without its own storage, and distributing it among the consumers. They are commonly called mini-grids or micro-grids. Mini-grids or grid operations, like any other business, must be economically attractive and their viability often depends on well-designed tariff regulations. In principle, revenues from the grid or mini-grid need to cover investment as well as operation, management, and maintenance costs. In addition to affordability of connections, stable revenues require both accurate predictions of electricity demand and matching consumers' electricity demand with the electricity supply as well as the tariffs for households, businesses, and public institutions. While subsidies may influence the average tariff, the affordability, and the scalability of mini-grids, they should be as high as necessary while being as low as possible. Different tariff systems can be deployed, ranging from flat-rate tariffs to pure energy prices or from energy- or power-based to service-based tariffs, as well as from progressive tariffs to regressive tariffs. Project economics plays a critical role in the viability of the grid or mini-grid operations.

A study from India indicates that the typical cost of generation from distributed generation is around INR⁴ 23–33/kWh based on the type of generation used in the micro-grid (Princeton University, 2014) against the average rural household spending of around INR 11/kWh to meet its lighting and other energy needs (World Bank, 2010). Another study on Bangladesh indicates that the levelised cost of generation for SHS and solar-diesel hybrid mini-grid ranges between US \$0.344/kWh and US \$0.715/kWh at the user end (Bhattacharyya, 2014). On the other hand, the typical regulated grid tariffs are much lower than the typical tariffs for mini-grids, as there is a cross-subsidy element in most cases. For example, the grid tariff is approximately 120 XOF⁵ per kWh for central grid in case of Senegal versus more than 500 XOF per kWh charged by private mini-grids (Ulsrud *et al.*, 2019). Similarly, in the case of India, private mini-grids charge INR 25 to INR 45 per kWh against the average grid tariff of INR 3.95 to INR 5.81 per kWh depending on the states (Gill, 2017). On the other hand, there are also cases where grid and mini-grid tariffs are competitive. For example, Cambodia's electricity tariff, which in 2016 was one of the highest in Southeast Asia with rural consumers paying US \$0.40–US \$0.80 per kWh, was only little lower than the mini-grid tariff, which ranged from US \$0.40–US \$1.25 per kWh (USAID, 2018). For consumers, whether electricity comes from grid or mini-grid makes no difference, so tariff parity is one of the essential elements; else the consumers tend to think mini-grid electricity is a temporary provision in the absence of grid and wait for the grid connection.

One way to address the issue is to attempt larger capacity mini-grids where cost of generation appears to be competitive. A recent study from Zambia shows that centralised solar generation when optimally located might produce generation/cost ratios as low as US \$0.042/kWh, comparable with existing hydro

⁴ 1 US dollar = INR 70.

⁵ 1 US dollar = XOF 590.

generation cost ratios of US \$0.02 to US \$0.03/kWh. The same study also indicates that a fully decentralised generation approach (whether off- or on-grid) is not economically feasible, as electricity is six to 12 times as costly as the existing rate. However, a hybrid option of centralised (70%) and decentralised (30%) was found to provide affordable power, as well as to enable quicker implementation (Ismail *et al.*, 2019). Another recently published study based on the mini-grid regulations in the state of Uttar Pradesh, India observes that low capacity mini-grids are not a viable proposition if the tariff prescribed in the state is used and that other cost minimising support (such as capital subsidy or low interest debt or an output-based subsidy) would be required to attract private investments. Large-scale solar projects or mini-grids, on the other hand, are more viable and can be an attractive proposition for rural electrification in the Indian context (Bhattacharyya *et al.*, 2019). Thus, to be commercially viable, a mini-grid model has to be based on an optimum (often large) consumer base. However, this raises a key question for the private sector: are there sufficient mini-grid sites in their target region or country for them to reach the optimum consumer base needed to operate a commercially viable mini-grid business?

Collecting sufficient revenue in rural areas is also more challenging than in urban areas because electricity demand and the ability to pay are lower. In some cases, rural populations themselves are unable to pay a tariff that reflects the full cost of electrification (Hunt, 2017). Regulators are, therefore, tasked with ensuring affordability and quality of service for (primarily rural) consumers on the one hand and, on the other, sustainable operation and cost recovery for private mini-grid operators. With the cost of generating electricity from mini-grids generally higher than from the national grid, in contexts where national uniform tariffs are applicable, viability gap funding often becomes necessary. Thus, a uniform tariff structure should be accompanied by well-defined plans for subsidising the mini-grid tariff (like government budgets, performance-based subsidies, cross-subsidies, or capital subsidies) to ensure economic viability. Tanzania's national utility sells electricity to isolated mini-grid consumers at a uniform national tariff to keep the consumer tariff low (USAID, 2018). In Bangladesh, the government provides half the cost of developing solar mini-grids as a grant with 30% of the balance given as a long-term loan. The remaining 20% has to be sourced by the project developers themselves. In some cases, regulators allow isolated mini-grid operators to set tariffs in consultation with local community members such that the tariffs are high enough to cover costs but aligned with consumers' ability and willingness to pay. Increasingly, regulators are taking a tailored approach to tariff regulation for mini-grids. Nigeria, Rwanda, and Tanzania, for instance, allow deregulated tariffs for mini-grids under certain capacity thresholds (e.g. under 100 kW in Tanzania). In India, the Electricity Act of 2003 allows mini-grid developers to enter into negotiated tariff with their consumers without the interference of the regulators (Palit and Bandyopadhyay, 2015). Larger mini-grids are also required to use standardised tariff calculation tools (such as the multi-year tariff order model in Nigeria) and tariffs need to be approved by the regulator. Indonesia and Peru have introduced a methodology for standardising tariffs to encourage private sector participation (IRENA, 2018).

5.2 Financing and ownership issues

Funding for mini-grids comes from both public and private sources, but it appears that funding has not been adequate to support their scale-up (Agenbroad, 2018; IRENA, 2018). Mini-grid companies have struggled to secure equity, or either concessional or commercial debt. In addition, any financing that is available is expensive, with rates of commercial debt available to developers typically 15% or more in sub-Saharan Africa (Agenbroad, 2018). Another associate risk is that local banks may often not be familiar with small-scale renewable energy, and they lack the knowledge to assess the risks associated with these projects. This is complicated by the fact that mini-grid projects generally require customisation; populations, loads, and renewable energy resources vary from village to village. Further, mini-grid assets in rural areas offer little collateral because they are difficult to repossess and have limited value when moved from their installation location (USAID, 2018b). Bhattacharyya (2013) observes that the estimates for energy access financing vary from US \$11 billion per year to US \$120 billion per year with a mid-range value of US \$50–60 billion for the next two decades. He further opines that both upstream and downstream financing options would play an important role for off-grid electricity supply. Rapid expansion of off-grid

electricity supply in remote rural areas would require expansion of financial services and financing options. While upstream finance receives greater attention, sustainability of the electrification efforts would also require a greater attention to downstream activities. Some agencies also observe that the enormity of the challenge is such that public financing will need to be complemented by private funding (NREL, 2015; ARE, 2018), while at the same time ensuring equitable services for the most vulnerable and marginalised communities. Thus, several governments have sought to attract private sector involvement in the mini-grid sector with a view to access additional financing, utilise capacity to deploy and maintain infrastructure assets over the long term, and encourage cost and technology optimisation (IRENA, 2016). Finding the right way of financing mini-grids, managing public investment, attracting private co-financing for the long term, providing public support via subsidy or result-based aid, and the efficient operation of the systems are complex and demanding tasks: a right balance must be worked out to ensure their viability and sustainability.

5.3 Risks, uncertainties, and mitigation

Reducing uncertainty around the arrival of the national grid is critical to the long-term viability of mini-grids. If defined ahead of time, interconnection and/or compensation mechanisms can allay associated risks. Countries such as Cambodia, Indonesia, Nigeria, Rwanda, and Tanzania (as well as some states in India) have introduced regulations that allow a mini-grid operator to relocate assets, sell parts of its assets to the utility, or become a small power producer selling electricity to the main grid at a fixed renewable feed-in tariff and/or become a distributor of electricity purchased from the main grid (IRENA, 2018). An important determinant of the success of such provisions is the tariff determination post-interconnection. If a compensation mechanism is mandatory, it provides a definitive exit option for mini-grid operators. In this case, the methodology for estimating the compensation (e.g. asset depreciation) becomes a key consideration. Access to a compensation option may also facilitate the negotiation of a fair power purchase agreement that allows the operator to cover both purchases from and sales to the main grid. Tanzania's compensation provision, for example, is limited to five years and covers only distribution assets, leaving significant elements of risk with the private sector. A point worth highlighting here is that end-users of renewable energy-based systems often compare the cost of electricity from a micro-grid to that of the main grid and are therefore prone to believe that expensive power is being sold to them. At present, also, the renewable energy systems operators do not get the benefit of tariff cross-subsidisation, which is available to most grid operator. The mini-grid sector will be ready to scale up rapidly once improved services can be offered at or below the monthly expenditure incurred on paraffin fuel or similar to the price of regulated tariffs.

6 Way forward

Our review of relevant literature has highlighted that, despite the proliferation of academic and practice-based studies focusing on-grid and off-grid technologies, there is no firm evidence to support the commonly held claim that off-grid options, particularly mini-grids, represent the least-cost option that will account for a major share of electricity access of hitherto non-electrified population. The planning studies, however, suggest that a combination of different technologies will have to be relied on for universal electrification, and the technology mix will to a large extent depend on the local context. While the planning studies have improved our understanding of the electrification challenge by using disaggregated data and developing spatially relevant least-cost solutions, there are several knowledge gaps in this area. These studies remain expert-driven and data-dependent. Data quality remains an issue and most of the studies have relied on a combination of sources of varying quality, as well as proxies where data is not available. Improved data are essential for better and more objective decision making. The technocratic approach to planning fails to capture the aspirations of local stakeholders and may not lead to the future they want. Moreover, some of the existing models do not have the capacity to capture productive loads

and integrate with other livelihood opportunities. The possibility of linking with other SDGs is also absent in these modelling frameworks. Further extension work in this area is possible.

To achieve universal electrification, a systemic approach covering planning, plan delivery, and governance arrangement is essential, but there is a significant gap in terms of adopting such an integrated approach in the developing world. The progress in academic knowledge does not appear to have influenced on-the-ground activities to a great extent. This suggests the need for capacity building efforts in developing the required skills and expertise at the national level. Translating a least-cost plan to an implementable programme involves several steps (such as prioritisation and identification of investment projects, detailed design of projects, project implementation, and project monitoring and evaluation), and an appropriate organisational arrangement is essential for access programme implementation.

The literature on governance arrangements for universal electricity access suggests there is no single template for successful implementation of such a programme, but a strong leadership and a supportive environment is essential. While countries have made progress in terms of developing the regulatory and governance arrangements, there are still gaps regarding the long-term vision about the electricity sector, the transition pathways for transforming energy access, and the possible interactions between different local and national systems. To what extent will different solutions coexist, and how will the interaction between grid and decentralised options (as well as the interactions between decentralised solutions) evolve in the long term, particularly in view of decarbonisation of the electricity sector? How can such a diversified and locally adapted solution be supported to promote sustainable development? In this context, the UK Department for International Development (DFID)-funded projects, such as Transforming Energy Access and Modern Energy Cooking Systems, are exploring energy-development linkages through the productive use of electricity and promoting clean cooking and mobility using renewable energy-based electricity services. Are mini-grid/grid infrastructures ready for such applications, and what will the effects of large-scale adoption of electricity for cooking and electricity for mobility be on-grid/mini-grid systems? Similarly, technological developments, particularly in artificial intelligence and telecommunication, have opened smarter ways of doing business. In the future, electric utilities in many countries will work towards developing urban micro-grids and peer-to-peer trading using block chains. Will the evolution of decentralised solutions lead to disruptive business models and signal an end to the central grid, or will the central grid consolidate its position by absorbing the decentralised solutions?

A supportive governance arrangement for electrification has received global attention, but the issue of large-scale implementation of such solutions to reach the electrification targets in a timely manner has not received adequate attention. A programmatic approach towards delivery of decentralised solutions is perhaps required to reach a wider section of the population quickly, but such an approach has not yet been effectively implemented. More importantly, achieving universal electrification by 2030 will require a large-scale implementation of electrification programmes at the national level that will include grid extension and accelerated delivery of decentralised solutions. How can national electrification plans be effectively implemented through programme design, development, and implementation and monitoring? There is need for further work in this area to investigate the design, feasibility, and organisational arrangement required to support a programmatic delivery option.

A sustainable electrification solution has to be affordable to the users, but the available evidence points to the relatively high cost of decentralised solutions compared to grid supply. This raises the issue of fairness, equity, and justice: why will some have to pay more for electricity than others living in a similar socioeconomic context? Is parity a desirable national objective for electricity supply? How could this be achieved? Further research is required on how costs for grid and decentralised solutions could be equalised/harmonised for consumers through internal arrangements to ensure that the technically better options do not lose out in terms of cost to serve. Moreover, the introduction of costly options into the electricity system has long-term implications for the sector, particularly in countries where the electric utilities are not financially strong. As the high cost of decentralised solutions derives from their inability to

exploit economies of scale and infirmness (especially for solar and wind), an alternative option has been suggested where relatively large-scale renewable energy capacity could be embedded at the distribution network level (Bhattacharyya *et al.*, 2019). The advantage here is the ability to capture scale economy that reduces cost as the capacity can be procured in bulk. Can large-scale renewable energy generation projects be embedded at the distribution network level in access deficit countries? How will this affect the utility technically and financially? The technical feasibility of such an option and whether this can address the issue of electricity access requires further investigation. An alternative approach could be to rely on bundling of projects over a larger geographical area (or spatial bundling). Studies of island-level electrification and the Remote Area Power Supply System in Bangladesh have adopted such a spatial approach. How can spatial bundling of decentralised solutions be effectively delivered? At what level of spatial bundling? What is the optimal spatial coverage for such a bundling? What are the implications of such a bundling approach for the utilities and national planning process? Further work on sustainable electrification and power system transformation is required.

The nexus between grid and decentralised solutions assumes importance for fragile and disaster-prone areas. Spyrou *et al.* (2019) argue that half the countries in sub-Saharan Africa appear in the top 50 fragile countries, and conventional electricity planning in such cases may not lead to optimal investment decisions. Although some recent studies have considered this issue (Patankar *et al.*, 2019; Spyrou *et al.*, 2019; Bazilian and Chattopadhyay, 2016), the issues here are not well understood. How does the risk affect the technology choice? The probability of targeting a central station or prominent network infrastructure may be high, but the decentralised solutions may also be equally affected due to high import dependency, lack of local supply chains, and damage to the local infrastructure. The private and public ownership of assets could adversely affect repair and replacement activities. Decentralised solutions may place the burden on individuals who may not be prioritising energy investment in the face of high uncertainty and risk of damage to the assets. The cost of capital for private investment may also be exorbitantly high. How can appropriate investment decisions be made in fragile states for enhancing electrification?

Similarly, the issue of resilient systems is gaining importance, particularly in view of the risk of climate-related disasters. A report by IRENA suggests that interconnected renewable mini-grids can enhance emergency response in disaster-prone areas (IRENA, 2016c). It has been suggested that standalone systems have proved effective in various disaster situations in the United States and Japan. Considering the disaster-prone nature of many developing countries, it is important to understand how a resilient electricity system can be developed. How could mini-grids and standalone solutions be used to offer effective response during the times of disaster emergencies? Are the local grids and infrastructure of decentralised systems (e.g. mini-grids) resilient enough in case of disaster?

Finally, there have been discussions over DC and AC systems. Opiyo (2019) opines, based on a comparison of DC-based versus AC-based mini-grids, that DC systems with decentralised power storage are more cost effective for rural electrification in sub-Saharan Africa. In this context, the International Electrotechnical Commission has also started working to develop system standards for DC. With growing access to computers, mobile phones, and DC lights, there is a potential to expand DC systems that can be supported directly by solar PV. Is it technically feasible and cost effective to switch to DC systems at the household level, in offices, and more broadly? Can a road map be developed for such a transition, and how will such a transition shape the future of the grid?

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Table A1: Summary of selected studies using HOMER

Sl. No.	Author	Case details	Technology option	Life and discount rate	NPC	CoE	Remarks
1	Shahzad <i>et al.</i> (2017)	Farm (137.488 kWh/day) and residential community (30.88kWh) in Punjab, Pakistan	PV (10kW), biomass generator (8kW), 32x167 Ah batteries	25 years, 10%	PK Rupees 4.48M	Rs 5.51/kWh	Grid supply @PK Rs 10.35/kWh more expensive
2	Fodhil <i>et al.</i> (2019)	20 households in South Algeria	PV (11.4 kW); diesel generator (6kW); battery 42 kWh	20 years, 8.25%	US \$67,083	US \$0.4/kWh	Productive load not considered, 47 kWh/day load used
3	Murugaperumal and Vimal Raj (2019)	A village in Pondicherry, India	PV (50kW), wind (10 kW), biomass (100kW), battery (800x 24Ah)	20 years, discount rate not indicated	INR 2.17 million	INR 10.14 /kWh (grid supply INR 5/kWh)	Standalone system is cost effective when located beyond 93 km from the grid. Primary, secondary, and deferred load were considered
4	Odou <i>et al.</i> (2020)	Fouay village in Benin	PV (150 kW), diesel generator (62.5 kVA), and battery 637 kWh	25 years, nominal discount rate 10%, inflation 2%	US \$555,492	US \$0.207/kWh (grid supply US \$0.22/kWh)	Considers household (372.9kWh/day), community (44.7 kWh/day) and commercial load (269.4 kWh/day), load variation by season is also considered
5	Ouedraogo <i>et al.</i> (2015)	Pissila village, North Burkina Faso	PV (150kW), diesel generator (90kW), battery	25 years, 8% real discount rate,	US \$1.495 million	US \$0.5/kWh	Household, community, commercial, and agricultural load (711 kWh/day)
6	Hossain <i>et al.</i> (2017)	Berjaya Tioman Resort, South China Sea, Malaysia	PV (700kW), wind (5x250 kW), diesel generators (400, 200, and 100 kW), battery	25 years, 8% discount rate, inflation rate 2%	US \$17.15 million	US \$0.279/kWh	Peak load 1185 kW

7	Lanre <i>et al.</i> (2018)	Health care facilities in Nigeria	PV/wind/diesel/battery or PV/diesel/battery hybrid systems depending on sites	25 years, nominal interest rate 11%, inflation 15%	US \$68,585 to US \$106,870	US \$0.207/kWh to US \$0.311/kWh	Health care facilities at six sites are considered. Load of 3.75kW is considered
8	Nnaji <i>et al.</i> (2019)	10 rural communities in Nigeria	PV, diesel generator, battery	25 years, 5.88 discount rate	US \$0.1 to US \$5 M depending on the system size	Between US \$0.4 and US \$0.55/kWh for energy efficient demand system	Analysed different communities with own load characteristics
9	Muh and Tabet (2019)	Southern Cameroon, rural area with 500 households, community, and commercial load	PV (67.3 kW), diesel generator (10kW), mini-hydro (13.4 kW), battery	Life 25 years, interest rate 12.5%, inflation 3%	US \$191.704	US \$0.443/kWh	Considered 10 alternative technology options for optimisation
10	Gebrehiwot <i>et al.</i> (2019)	Remote rural village in Ethiopia for electricity supply to households, institutions, and a church	PV (20 kW), wind (3x3 kW), generator (5kW), battery	20 years, 7% interest rate	US \$82,734	US \$0.207 /kWh	Load data is based on a survey
11	W.M. Amutha, V. Rajini (2016)	A village called Kadayam in Tirunelveli district, Tamilnadu, India where electricity is demanded for domestic purpose, industrial/commercial activities such as milk processing plants, schools, shops, hospitals,	Solar (22.5 kWp)/wind (30 kWe)/hydro (7.5 kWe)/battery hybrid system	20 years, interest rate not available	US \$ 162,987	US \$0.111/kWh	Considered seven alternative technology options for optimisation

		street lights, etc., and for a Base Trans-receiver Station (BTS)					
12	Micangeli <i>et al.</i> (2017)	Habaswein hybrid off-grid power station situated in North eastern Kenya (Wajir County)	Diesel generator (410 kW, a 30 kWp SPV, and a wind farm (3 x 20 KWe))	25 years; discount rate 10% and inflation 8%	US \$ 6,179,443 to US \$ 6,507,321	0.253 to 0.305 US \$/kWh	Considered limited and optimal Battery Energy Storage System (BESS)
13	Sen and Bhattacharya (2014)	Kondagaon project near Palari village in central Indian state of Chhattisgarh	SHP 30 KWe), solar PV (20 kWp), bio-diesel 10 kWe), and batteries	25 years; 10% annual discount rate	US \$ 6,73,147	US \$0.420/kWh	
14	S. Salehin <i>et al.</i> (2015)	Char Parbotipur island, Kurigram district in the northern region of Bangladesh	Solar PV (14.4 kWp), diesel generator (4 kWe), battery power system		US \$149,112	US \$0.461/kWh	

Source: Authors

Table A2: Selected Network Planner studies

ID	Author	Country case	Optimal solution			Investment need	Comment
			Grid %	Diesel mini-grid %	Standalone %		
1	Ohiare (2015)	Nigeria, electrification by 2030	98%	2%		US \$34.5 billion	Average LCOE of grid supply US \$0.33/kWh; mini-grid 0.47/kWh. The analysis was done at the local government areas. Granularity of data is limited. Demand of 330 kWh/year/household is used

2	Kemausuor <i>et al.</i> (2014)	Ghana, 2,600 non-electrified communities	85%	8%	7%	US \$696 million	Grid LCOE US \$0.57/kWh; Diesel US \$1.02/kWh and standalone US \$1.12/kWh; 150 kWh/year/household demand for a community with less than 500 population
3	Akpan (2015)	Taraba and Yobe states of Nigeria	98.7% Taraba; 89.5% Yobe	1.3% Taraba; 10.5% Yobe	0% in both states	US \$6.56 billion for Taraba and US \$7.02 billion for Yobe	LCOE of grid supply US \$0.18/kWh; diesel US \$0.20/kWh; Assumed household demand of 1662.75 kWh/year, productive demand of 287.04 kWh/year, and social infrastructure demand
4	Sanoh <i>et al.</i> (2012)	Senegal national- and local-level electrification planning	49.1%	13.6%	37.3%	Not reported	Considered a target of 70% electrification over a 10-year horizon. Connection cost per household: Grid US \$1,048, diesel 850, PV 723. Four demand categories by village population size were considered (<500, 500–1,000, 1,000–5,000, and >5,000 population) taking four types of demand (household, school, health centre, and productive load) for each category
5	Parshall <i>et al.</i> (2009)	Kenya national plan	96% in full penetration case	n/a	n/a	US \$6 billion in realistic case	Cost of grid connection per household US \$1,907. Used four demand categories: sparse-poor (360 kWh/household/year, productive demand 50 kWh/year), sparse-non-poor (600 kWh/household/year, productive demand 100 kWh/year), urban-poor (360 kWh/household/year, productive demand 75 kWh/year), urban-non-poor (1800

							kWh/household/year, productive demand 340 kWh/year)
6	Modi <i>et al.</i> (2013)	Liberia	90%–95% of the population	5%–10% of the remaining population		US \$1 billion for grid extension, US \$70 million for decentralised options	LCOE for grid electricity US \$0.2–US \$0.21/kWh; diesel mini-grid US \$0.63–US \$0.64/kWh standalone PV US \$0.73–US \$0.74/kWh Used five demand categories: poor (600kWh/year), low income (2,280 kWh/yr), middle income (5,172 kWh/year), upper income (9,768 kWh/yr), high income (25,188 kWh/yr)
7	ADB (2016)	Sumba Iconic Island, Indonesia	77%	3%	20%	Mini-grid US \$6.6 million; off-grid US \$43.1 million; grid US \$450 million	This is an example case provided in the report. The study has also used HOMER and load flow analysis packages for a detailed analysis

Source: Authors

Table A3: Review of OnSSET applications

ID	Author	Country case	Optimal solution (of population)			Investment need	Comment
			Grid %	Diesel mini-grid %	Standalone %		
1	Mentis <i>et al.</i> (2015)	Nigeria, electrification by 2030	85.6%	13.1%	0.3%	US \$15.4 billion	Used multi-tier framework; Levelised Cost of Electricity (LCOE) varied between US \$0.15/kWh for grid connection to US \$1.4/kWh for electrification in remote locations. Demand used for rural areas is 170 kWh/year/capita and 300

							kWh/year/capita for urban households
2	Korkovelos <i>et al.</i> (2019)	Malawi	32.6%	0%	67.4%	US \$1.83 billion	Cost of grid connection is US \$981/household; cost of standalone PV/ household is US \$118. Rural demand used is Tier 1 and urban demand is taken as Tier 4
3	Moksnes <i>et al.</i> (2017)	Kenya, OnSETT, and Osemosys analysis	53%	47% (split not reported)		US \$21.4 billion	LCOE US \$0.08/kWh for grid, US \$0.42/kWh for standalone solutions. Two demand scenarios considered: low demand (rural 43.8 kWh/person, urban 423.4 kWh/capita), high demand (rural 423.4 kWh/capita, urban 598.6 kWh/capita). Low demand scenario results reported here
4	Mentis <i>et al.</i> (2017)	Sub-Saharan Africa	Low: 20% High: 78%	Low: 0% High: 16%	Low: 80% High: 6%	Low: US \$50.32 billion High: US \$1282.48 billion	Continental level analysis using country-level data, considered 10 load scenarios. Low refers to lowest demand scenario, high refers to highest demand scenario
5	Mentis <i>et al.</i> (2016)	Ethiopia	93%	6%	1%	US \$9.4 billion	LCOE US \$0.12/kWh for grid extension, US \$1.74/kWh for remote standalone diesel generation; demand for rural areas taken as 150 kWh/capita/year and 300 kWh/capita/year in urban areas
6	Korkovelos <i>et al.</i> (2017)	Afghanistan, 12 scenarios of electrification	Low: 27.3% High: 60.7%	Low: 2% High: 38.3%	Low: 70.7% High: 1%	Low: US \$8.28 billion High: US \$25.76 billion	Tier 5 (4,190 kWh/household per year) for urban households and Tier 3 (1,301 kWh/household/year) for rural households are assumed as the target level of electrification by 2030

7	Kappen (2019)	Madagascar – high level least-cost overview	25%	18%	57%	US \$3.2 billion	The project information document provides limited information on the least-cost study
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Source: Compiled by the authors.

Table A4: Selected case studies using REM

ID	Author	Country case	Optimal solution (of population)			Investment need	Comment
			Grid %	Mini-grid %	Standalone %		
1	Ellman (2015)	Vaishali (India)	0	85%	15%	US \$45 million/year	Used the case to demonstrate the application of the model at the local level
2	Amatya <i>et al.</i> (2018); Ciller <i>et al.</i> (2019)	Large representative case with 52000 consumers	51%	17%	32%	US \$15.02 million /year	US \$0.206/kWh for grid extension, US \$0.312/kWh for mini-grid, US \$0.313/kWh for standalone systems. 17 load categories were considered including residential. Commercial and productive loads based on data from a village survey in Rwanda. Peak demand of low-income households is taken as 0.08 kW and that of high income households is taken as 0.4kW
3	REG (2019)	Rwanda country study (reference case 2024 electrification)	52%	27%	21%		US \$0.199/kWh for grid extension; US \$0.593/kWh for micro-grids; US \$0.4/kWh for standalone systems Two residential consumer types are considered: Type 1 (<10Wp) and Type 2 (<50Wp).20 categories of productive and institutional loads are also used

4	Gonzales-Garcia <i>et al.</i> (2016)	Michiquillay, Cajamarca department in Peru	0%	80.5%	19.5%	US \$10.7 million	LOCE mini-grid US \$0.85/kWh Standalone supply US \$1.19/kWh Base case scenario used a basic level of supply (two lights, one mobile charging, and options for an additional light, a fan, and a television connection). The average load is 21.07W and the peak load is 75.75W. Average annual consumption is 185.5kWh
5	Mwalengi <i>et al.</i> (2016)	Kilifi county, Kenya	3%	97%	0%	US \$4.66 million per year	LCOE for grid supply US \$0.46/kWh; Mini-grid US \$0.62/kWh Peak demand of 75W per household is used

Source: Compiled by the authors

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