A critical review of literature on the nexus between central grid and off-grid solutions for expanding access to electricity in Sub-Saharan Africa and South Asia

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Abstract

This paper critically examines the literature on the grid-offgrid debate and discusses the role of and the relationship between different electricity access options through a synthesis and critical reflection. This paper finds that models using greater resolution and capturing low voltage distribution infrastructure appear to recommend decentralised electricity solutions, whereas central grid extension emerges as the preferred outcome of more aggregated analysis, concentrated population clusters and for higher demand scenarios. However, model results are seriously influenced by assumptions, data limitations, technology choice options, and model flexibility. Exclusion of cost of generation for grid systems, lack of village level information, inherent bias towards scale and type of technology, and absence of social equity considerations in the analysis remain major weaknesses of the existing models.

Universal electrification requires a strong leadership and an enabling environment. An appropriate organizational set-up, a robust regulatory framework with reporting and evaluation oversight and a more inclusive approach to promote alternative options are vital ingredients. Power sector decarbonisation pathways may affect electrification choices but our understanding is limited or lacking. Further work is required to develop a programmatic approach to delivery and more affordable and fairer outcome for all.

Highlights

- The paper presents the up-to-date review of the debate on grid and off-grid electrification.
- We find a strong leadership and an enabling environment is essential for universal electrification by the year 2030.
- Appropriate organizational set-up, robust regulatory framework and shift from grid-centric focus to a more inclusive approach to promote alternative options is equally important
- Important to develop a programmatic approach to delivery and more affordable and fairer outcome.

Keywords

Rural electrification planning; electricity access, HOMER; Network Planner; OnSSET; electricity regulations

Word Counts

Approximately 9922 words (including footnotes but excluding References and Tables)

Abbreviation

ESMAP – Energy Sector Management Assistance Program

HOMER - Hybrid Optimization of Multiple Energy Resources

IEA – International Energy Agency

IRENA – International Renewable Energy Agency

REM - Reference Electrification Model

OnSSET - Open Source Spatial Electrification Toolkit

SDG – Sustainable Development Goal

1. Introduction

Access to energy constitutes the crucial link between three dimensions of sustainable development (i.e. social, economic and environmental) but the global efforts towards a sustainable future are at a peril with around 990 million people without access to electricity and around 2.7 billion lacking access to clean cooking energy in 2017 [1].[1] The problem is more acute in sub-Saharan Africa and South Asia where the greatest number of people without energy access are found and the problem affects the rural and low-income population the most.

Energy access has received recent global attention, particularly with the launch of the Sustainable Energy for All in 2012 and the Sustainable Development Goals in 2015 (Goal 7.1 deals with energy access) to be achieved by the year 2030. However, the progress with the delivery of energy access has remained slow in comparison to population growth. According to IEA and the World Bank, 87 million people gained electricity access between 2012 and 2014 [2] but most of them (81 million) were from urban areas and the rural electricity access for 6 million was below the rural population growth. The problem is more pronounced in sub-Saharan Africa, which in turn requires further attention for reaching the bottom billion [3].

Achieving the objective of universal energy access by 2030 would require a significant acceleration of efforts by countries, particularly those in the low-income category, which tend to be more vulnerable and highly indebted. A modal shift is required to scale-up from the current demonstration projects to accelerated programmatic deployments [4]. The accelerated delivery of energy access to reach billions of population within a limited time period and subject to resource constraints remains a challenge. There is also an opportunity for energy access interventions to catalyze sustainable rural development through better linkages

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[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 [5]

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, energy access requires an integrated approach and in the context of electrification, the respective roles of central grid expansion, mini/micro-grid based electrification and off-grid electricity solutions need careful consideration.

Through a detailed literature review, the paper attempts to highlight the relationship between grid and off-grid electrification by identifying emerging trends and suggesting priority research questions for expanding and sustaining electricity access. Specifically, this paper is addressing the following research questions:

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

The above questions are answered in the following sections, with Section 2 outlining the methodology followed while Section 3 offering a critical review of literature on centralised grid versus decentralised off-grid options. Section 4 discusses the enabling and supporting environment in terms of policy and governance issues whereas Section 5 deals with project economics, finance, and risks. Finally, Section 6 discusses the way forward and possible areas for further research.

2. Methodology

A critical review of available literature (academic and non-academic) was undertaken, and a selection of background reading materials was gathered using keyword searches on the internet and document records in various journal databases as well as technical reports from agencies such as the World Bank, IEA, IRENA, among others. Search queries included words and word combinations such as “central grid electrification”, “distributed generation”, “rural electricity services”, “rural electrification”, “electricity access”, “off-grid”, “decentralized electricity system”, “stand-alone systems”, “decentralized renewable energies”, “solar PV”, “solar mini-grid”, and “techno-economics”. A total of 106 publications, consisting of 59 articles from scholarly journals and books (56%), 44 technical reports (41%) and 3 dissertation/thesis (3%) related to the subject, were reviewed. More than 60% of the articles and reports considered were recent and were published as of 2016. 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 (Figure 1). The authors also relied on critical thinking and meta-analysis of the available knowledge to develop the main arguments of this paper.

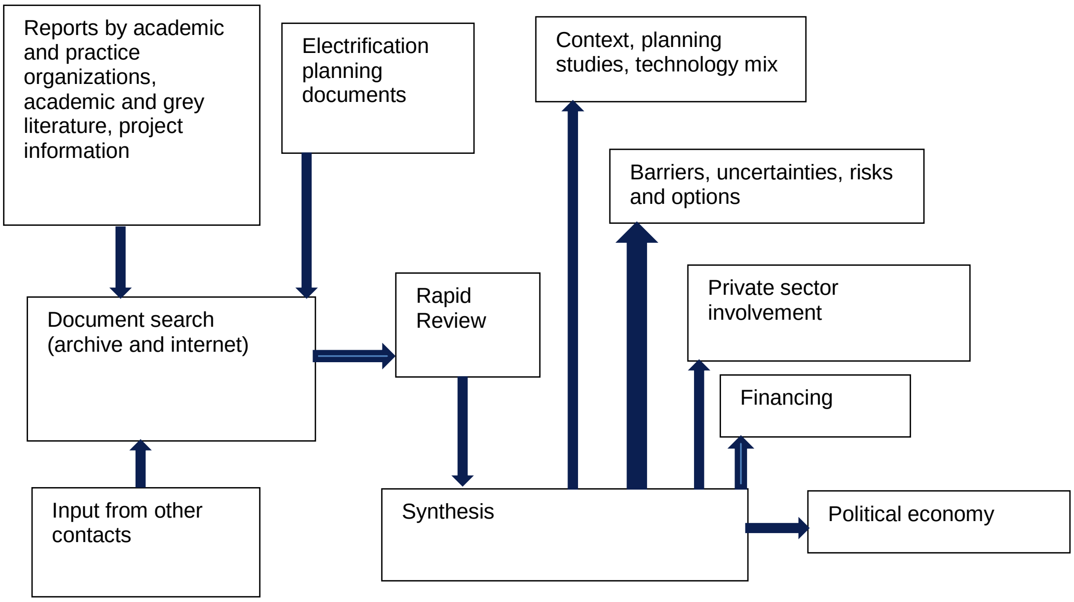

Figure 1: Schematic of the literature review process

Source: Authors

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

The academic and practice-oriented literature on rural electrification is well developed. Studies have categorised this literature into different strands: this has been placed under three categories in Figure 2 [6-8].The first category has a techno-centric focus capturing technical systems, tools and even practice-oriented literature. The second category adds modelling of electrification planning to the previous category and offers some consideration to energy access and economic development agenda. The third category further extends the second category by including policy related studies. But case studies of specific systems and techno-economic analysis remain very widespread. A recent study [9] offered insights into the role of grid versus off-grid options in the South Asian context through a comparative assessment of the levelised costs of electricity and the impacts on the countries in supporting rural electrification.

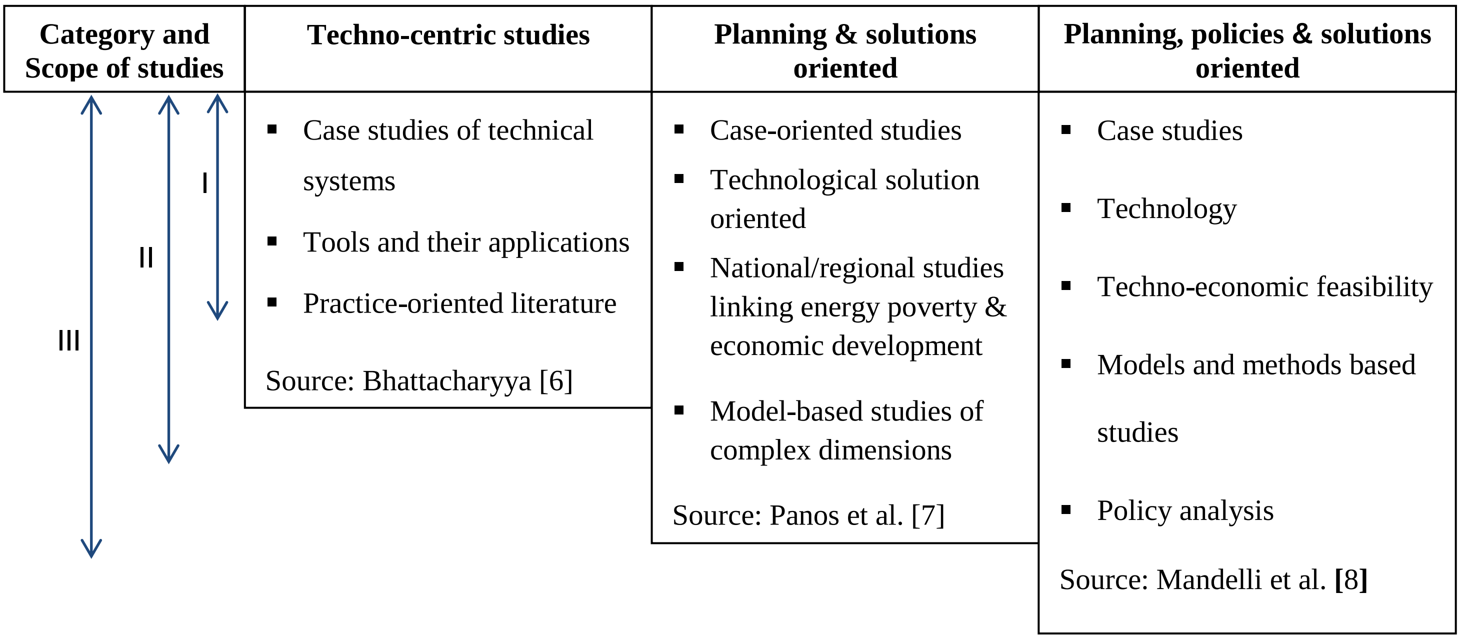

Figure 2: Categories of energy access literature

Rojas-Zerpa and Yusta found 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 [10]. They also reported 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 observed that the planning horizon for most of the studies remains short- to medium-term and only limited attention has been given to long-term planning. 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 that includes identifying appropriate technology for a given context, assessing economic feasibility, and finding a suitable support package to ensure commercial attractiveness of a project [11]. Most often, these studies consider the off-grid option explicitly. The possibility of grid extension is considered through cost comparison, without overtly considering the possibility of grid extension. Electricity planning studies have relied on identifying the least-cost option through an optimization process. Although some studies have relied on their own formulation of the optimization problem (e.g. [12, 13]), the proliferation of case studies could be attributed to the availability of standard software packages like Hybrid Optimization of Multiple Energy Resources (HOMER).

An IEA study in 2011 observes that for universal electrification, expansion of central grid is the most effective option for urban settlements and 30% of non-electrified rural areas. However, for the remaining 70%, decentralised solutions are better choices with mini-grids and standalone solutions occupying a 65:35 market share [14]. This figure has dominated the discourse for almost a decade before it was revised recently to 50% of the rural population [15]. However, 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

There are a growing number of studies that have reported least-cost off-grid electrification options using HOMER. Relevant information of a selected set of recent studies is presented in Table A1 and a critical review based on these studies from a diverse set of countries leads to the following observations:

- The analysis reported in many of the studies represents the techno-economic feasibility of project ideas and is not about real projects. There is a dearth of studies revisiting the optimal technical choice of real projects using HOMER. Exceptions include, among others, the study by Chmiel and Bhattacharyya, who investigated off-grid intervention implemented in the Isle of Eigg, Scotland [16], and the study by Singh and Balachandra of a PV-biomass gasifier project from an Indian village [17].
- 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. Interestingly, comparison on a 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.
- 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 in most cases and include various combinations of end-use appliances as per their relevance in the case study areas.
- The technology cost is often sourced from international references, in foreign currencies, and either local market conditions are not well reflected or data from actual projects were not used. Further, there is significant variation in terms of discount rate choice.
- The cost of electricity supply reported in most cases remains generally high, varying between US \$0.207/kWh to US \$0.5/kWh, although the chosen option is the least-cost option among other alternatives.

Cader and others 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 [18]. 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 different levels (local, national, and regional levels). Local-level studies include the study by Quinonez-Varela and others who explored the grid integration of renewable energies in Scotland [19]; and the study by Sahai who presents an example of planning for Indonesia highlighting the case of an island [20]. The later study also suggests grid extension for 66% of the population of the island, followed by mini-grids for 33% and standalone solutions for 1% [20]. National-level studies include studies by Castalia Strategic Advisors [21] and Deloitte [22]. Castalia used a spread sheet model linked with a database, based on Geographical Information System (GIS), to analyze the technology choice for electricity access in Rwanda and found that expansion of central grid costs the least for 95% of the population; off-grid micro-hydro systems are suitable for 4.5% of population, and standalone systems for the remaining population [21]. Deloitte on the other hand analyzed the electrification plan for Zambia using open source software developed by USAID's Southern Africa Energy Program and suggests that if all households are electrified by 2022, then solar home systems (SHS) would account for 75% of the population and 25% would get electricity through grid extension [22]. As per the same study 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 and others reported the case of the universal electrification of Burkina Faso [23, 24]. They suggest that, out of 10.8 million people in non-electrified areas, grid expansion will cost the least to provide electricity for 4.4 million people, whereas decentralised solutions are cost effective for the remaining population. In already electrified settlements, grid extension is cheaper to provide electricity to those lacking access (3.9 million). However, PV systems will be the cheaper option for 0.8 million rural people. Some of these researchers analyzed the case of Kenya and compared model outcomes with the electrification master plan prepared by the national electricity company [25]. While the master plan aims at extension of diesel generation for non-grid areas, the model simulations suggest 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 the two studies: the master plan assumed €3.5/Wp (US$ 4.2/Wp) for PV, whereas Moner-Girona and others used €1/Wp (US$ 1.2/Wp) [25][2]. A report about the costing of PV projects in Africa by IRENA, however, 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) [26].

At the regional level, Szabo and others presented an analysis of different options for electrification of sub-Saharan African countries [27]. The analysis considers standalone solar PV, diesel mini-grids, and grid extension options. The study finds that expansion of grid only becomes viable for locations with a high number of consumers. PV becomes the most attractive technology for levelised costs between €0.25 (US$ 0.3) and €0.3 (US$ 0.36) per kWh. However, the study also suggests that, over large regions neither diesel generators nor PV offers affordable electrification solutions. In a subsequent study, Szabo and others introduced mini-hydro as an additional technology and compared its cost effectiveness with central grid expansion [28]. They suggested that removing diesel subsidy will reduce the importance of diesel generation. Huld and others combined geospatial analysis with PV mini-grid performance optimization covering Africa and Southeast Asia and suggested 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 [29]. This highlights the importance of local conditions for mini-grid system design.

We now 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

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[2] 1€ =1.2 US$.

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. [18, 23, 25, 27, 28]) have been captured in the paper at relevant places.

The Network Planner, a web-based tool developed at Columbia University by the Modi Research Group, has been widely used to explore the grid versus off-grid choice. The model compares grid extension with diesel based mini-grids and standalone solar PV. The tool 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 (refer Table A2). Its ease of use has facilitated a number of applications in developing countries such as Ghana, Kenya and Nigeria (refer to Table A2 for additional details).

A critical analysis of the information in Table A2 leads to several observations. One of the main observations 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 is important to mention here that, for central grid supply, the tool considers only the cost of network infrastructure development and does not include the cost of incremental generation. This assumption may not hold in many cases. The network maintenance cost is usually taken as a fixed value of the capex and this may underestimate the grid supply cost.

The Network Planner model can deal with large volumes of spatial data, but it has several limitations. For example, the technology choice is limited, which often influences the results. The mini-grid technology option considers only diesel-based mini-grids. As the running cost of diesel generators is high, the mini-grid option proves less favourable to grid extension. The declining prices of PV panels and modular design of solar PV mini-grids were not considered in these studies, thus limiting 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 used data from the local government, not at the village level [30]. As 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 different outcomes. In addition, the studies could not take advantage of cost reduction in solar PV mini-grids, which has limited the possibility of lowering their cost of supply. Salam and Phimister argue further that efficacy of the heuristic algorithm used in Network Planner deteriorates as the dispersion increases and the remoteness of the habitations increases from the central grid system [31]. This creates a systematic bias towards grid extension in the model.

The OnSSET model has been used for many developing countries (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.

A critical review of the information provided in Table A3 leads to the following observations:

- 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 systems play a critical role. A study on Malawi [32] 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 studied cases. 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. 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. Amatya and others explained that the model performs least-cost electrification design by identifying the optimal technology option at a high level of spatial granularity [33]. Ellman described the logic used in the model, data requirement, and calculation principles [34]. Like the Network Planner and OnSSET, REM identifies grid-off-grid choices, but it also designs the micro-grid system and the local network (refer Table A4). Drouin argued that, in terms of user-friendliness, the Network Planner is better than OnSSET or REM, but REM and OnSSET have better technology choice capabilities [35]. REM has a higher level of granularity in the sense that it can consider household energy demand and can also design the grid network down to the household level. Further, REM could be applied to different cases—local, regional, and country levels. While the Vaishali district in Bihar, India example given in the study by Ellman [34] appears to have been the first application of the model at a local level, the study by REG is an example of country-level application [36]. Although the model appears to be very comprehensive, it has not been very popular in terms of application.

Further insights can be obtained by comparing results obtained from different models (e.g. the Network Planner, OnSSET, and REM) for a given country. For Kenya, using Network Planner, Parshall and others suggested that, in the scenario of realistic grid penetration, 41% of the households would get connected to the grid by 2030, but in the full penetration scenario this increases to 96% over the same period [37]. Expansion of grid costs the least in densely populated habitations where the 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 and others 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 [38]. The investment requirement is estimated at US $21.4 billion. Mwalenga and others, using REM, suggests that 96% of households in Kilifi in Kenya could be connected via mini-grids [39]. There is no national-level study using REM but, going by this case study, the emphasis on mini-grids is clear.

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

- The studies considered in the previous paragraphs were undertaken at different times using different datasets. Parshall and others relied on data available around 2007 [37]. On the other hand, Moksnes and others relied on data from 2013 onwards [38]. Mwalenga and others used data from 2012 [39]. 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, particularly using surveys. Blodgett and others compared electricity use predicted by surveys for eight rural mini-grids in Kenya with the actual consumption and questioned the reliability and accuracy of surveys [40].
- 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, maintenance 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.

3.3 Review of electrification plans

A review of national electrification plans of 20 countries in Ref. [41] that have the largest number of un-electrified houses indicates 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 [41]. The table is based on simple observation of existence of a rural electrification plan, an investment budget and an electrification policy. The commitment for decentralised electrification is ascertained considering the existence of an investment budget and/or existence of a policy instrument. Further, in most countries, decentralised electrification has been considered to supplement the areas where grid expansion is daunting. This shows that distributed electrification is not considered a universal approach in the planning of electrification strategy (Table 1).

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

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

Note: Commitment to decentralised electrification is ascertained by observing the existence of an investment budget and/or existence of a policy instrument for the same. Existence of a national plan, an investment budget and a policy instrument is checked with a X in other three columns.

Source: Based on [41]

The United Nations Conference on Trade and Development (UNCTAD) remarked that countries such as Lao 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 [42]. Realizing this gap between practice and the state-of-the-art knowledge, Sustainable Energy for All has called for full-systems approach to electrification adopting a five-stage process (Figure 1). As can be observed from Table 1, mere existence of plans, budgets and policy instruments do not ensure successful electrification. At least 10 countries in Table 1 implemented these basic requirements. Yet, all of them have significant electricity access issues. Accordingly, a systemic approach to electrification, as indicated in Figure 3, is desirable, although implementation remains a challenge, and one has to see to what extent such a process is practically adopted by the concerned countries.

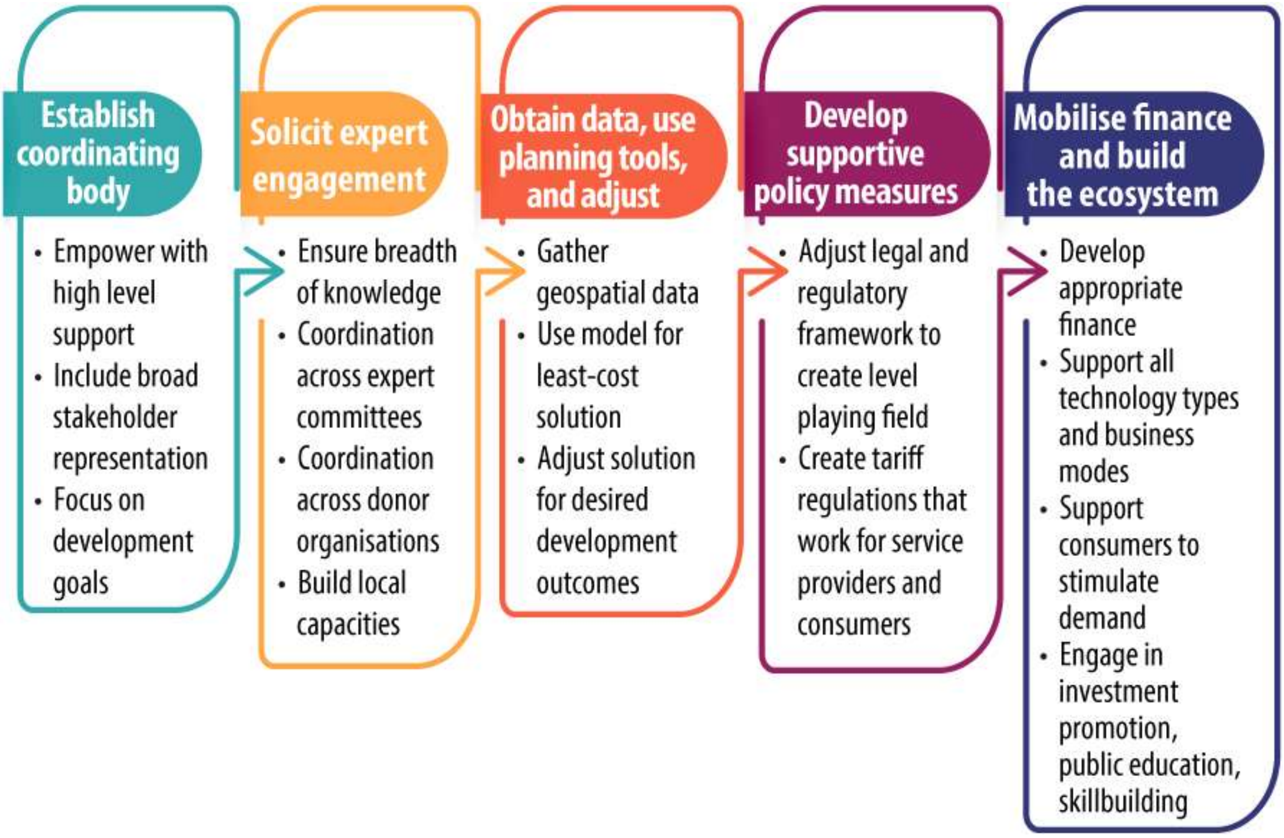

Figure 3: Process map for an Integrated Electrification Pathway

Source: [44]

3.4 Takeaways from the reviews

Our critical 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. 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. 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, there is hardly any attention given in the literature to the planning of large programs. 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 program, although some researchers and agencies provide relevant planning frameworks [43, 44]. Efforts need to move from local plans and pilot projects to country-level plans and mass rollout of programs to ensure electricity supply with fairness and equity to all, given the inherent socio-economic disadvantage of populations living in rural and remote regions. To make this happen program-level synergies, standardization, and appropriate planning processes are required.. In addition, prioritization of investments, considering funding constraints, human resource scarcity, and administrative and other considerations has not been given attention so far. The absence of planned efforts may be due to funding constraints on implementing national-level programs or to a lack of vision and adequate information in specific countries.
- **Role of decentralised options:** although claims are often made that decentralised options are least-cost solutions for most population lacking access to electricity [45], 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 case examples. The results of the planning studies are inconclusive, and most appear to suggest a mixed-bag approach where both grid and off-grid technology solutions will play a role. 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 [46]. 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.

4. Review of the enabling environment for different electrification options

4.1 Fundamental principles for successful electrification

From the previous section, we observe that universal electricity access will rely on complementarity of centralized systems and off-grid technologies. Review of success stories of countries that have achieved near-universal electrification also shows that there is no single template for success, and that all countries have used ‘home-grown’ models. Nevertheless, these cases suggest four basic principles for the planning, design and success of electrification program implementation [47, 48]:

1) A visible and committed political leadership or government;
2) An enabling and supporting institutional environment;
3) Adequate and sustained financing; and
4) Wider stakeholder engagement and coordination.

As a first step, a strong government commitment and leadership is essential for setting the electrification target and developing a program. Successful countries have pursued the electrification policies over decades and such a long-term government commitment and clear vision was a prime feature of success in China, Thailand, India, and Vietnam [48] Further, the vision must indicate deliverable targets and appropriate standards and benchmarks on the tiers/levels of electricity access as well as service quality [42].

Next, an enabling governance institutional structure is critical to define the ownership structures, duties, and responsibilities of different actors and the operation of the electricity sector [42]. The organizational 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 [42]. Some researchers 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 of better data is a prerequisite for success in energy access delivery [49].

From an organizational perspective, a national entity for overseeing the electrification program and harmonising the efforts of different stakeholders is required. It is important for such an entity to have clear roles and responsibilities, 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 [48].

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 [48]. However, the regulatory capacity is a challenge in most developing countries.

4.2 Mainstreaming off-grid solutions

Mainstreaming off-grid/ mini-grid solutions within the national power sector plans is an important first step to enable the development of the sector. This also provides the necessary incentive to stakeholders to work out custom-made solutions to enhance access. Many countries have considered different approaches and introduced targets for covering unserved and underserved communities using off-grid and mini-grid solutions to complement central grid connections. By 2016, out of the one billion people who had been provided with electricity connections since 2000, stand-alone or off-grid renewable energy systems have impacted about 133 million lives of people. While the overall share may be low, the recent growth has been enormous. From the year 2008 to 2016, the population served from mini-grid systems tripled to almost 9 million across Asia and grew six-fold to 1.3 million across sub-Saharan African countries [50]. Schnitzer and others give many cases of operational mini-grids from Haiti, India and Malaysia implemented by governments, private developers and not-for-profit organisations [51]. A study by United Nations Industrial Development Organization provides instances of operating mini-grids in six sub-Saharan African countries, namely Chad, Cote-d'Ivoire, Gambia, Guinea-Bissau, Tanzania and Zambia and two Asian countries - India and Sri Lanka [52]. Yet another study provides a thorough analysis of PV & hybrid mini/micro-grids in Senegal. The study discussed the role of international and national framework conditions, emerging innovation systems and socio-technical transitions to clean technological solutions [53]. Earlier, authors of this paper have also provided detailed analysis of several case studies from South Asia [54].

An analysis of different studies indicates that there are mainly four different types of ownership and operator models for mini-grid projects. They are: (i) utility owned and managed models; (ii) privately owned and managed models; (iii) community-centric models; and (iv) hybrid operator models [50, 55, 56]. These models differ with respect to ownership of the generation and grid network, operator and system maintenance, and how the operator and the consumers are related. One cardinal requirement for success, irrespective of the operating models, is an enabling policy and regulatory regime. However, as highlighted in Section 3.3, not many countries have policy instruments or allocated budget for decentralised electricity systems [41].

An enabling policy and regulatory framework, along with other aspects (such as technical, social 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 to consider in the off-grid/mini-grid sector include, among others, clarity in legal, regulatory and licensing requirements, tariff regulations, financial support mechanism, quality benchmarks, and finally inter-connection with the central grid if it is extended to the settlements or mini-grids is set up in grid connected areas that have reliability challenges [57, 58]. Furthermore, the lack of a clear policy environment increases the uncertainty and deters private investments [50]. With most mini-grids offering electricity for fixed hours in the evening and/or for meeting only low consumptive loads like lights and mobile phone charging, many consumers tend to prefer main electricity grid due to higher availability of load and even that at a lower regulated price of electricity [59]. Whether electricity is supplied from the centralized main grid or from decentralised solar PV, the important consideration for the consumers is that it should be readily available for meeting the demand, and be reliable and affordable. Unless this consumer related aspects are considered, the possibility of mini-grids becoming stranded assets is high after central grid is extended. Thus, for mini-grids to thrive alongside the centralized grid they will have to match or better the grid – in terms of cost-competitiveness and meeting the desired load in addition to the reliability of services that they are already offering to consumers – while generating enough revenues to operate sustainably. Some initial research do indicates such possibilities like better designing, coupled with lowering of costs of solar panels and storages, the consumers' demand can be met at a competitive tariff (for more refer section 5.1 on project economics).

The mini-grid policies and regulations, however, vary significantly across different countries. While some countries have recently started to consider mini-grids as an option to their improve rate of rural electrification, some are successfully running hundreds of mini-grids (e.g. Bangladesh, Cambodia, India, Nepal, Tanzania, among others). In general, regulatory agencies are struggling to address the needs and concerns of different sector stakeholders. Immature policy and regulatory frameworks continue to create difficulties for mini-grid developers, electric utilities and consumers. There are instances where governments have not yet defined the regulatory authority over mini-grids (e.g. in India) or framed clear set of regulations and/or performance benchmarks. The regulations that are framed for large countries that are mostly government-owned or the private sector owned systems are usually not appropriate and suitable for smaller mini-grid projects. The regulatory institutions, overseeing the sector, have often developed unclear regulations, which have resulted in inconsistency and non-clarity on how the sector could be regulated [50].

The Regulatory Indicators for Sustainable Energy (RISE) global report, published by the World Bank in 2018, indicates large improvement in policies related to sustainable energy globally. The number of countries that have advanced policy frameworks for sustainable energy has more than tripled during the last decade [60]. Interestingly, the same report indicates that, over the same timeframe, the supporting environment for central grid electricity access continues to remain same and now scores lower with respect to the off-grid energy technologies. Despite the improvement in the policy sphere, the RISE report also highlights that the world has only reached half way towards the development of advanced policy frameworks in the sustainable energy sector. This puts at risk the objective of achieving the SDG7 by the target year. Further, policy enforcement appears to be a major challenge. While strong and enabling policies are extremely important, they must be supported by empowered institutions and implementation of the policies. Among the different regions, sub-Saharan Africa has most weak regulatory framework, with almost half of the countries in the region not having a fully developed framework [60]. However, some countries within the region, such as Ethiopia, Rwanda, Tanzania, and Uganda, show a green rating[3] for their policy environment.

To capture the developments and inform policymaking, IRENA launched a report in the year 2016 outlining different policies and regulations existing for the privately led minigrids with the objective of analyzing the design elements of dedicated mini-grid policies being introduced in developing Asia, Africa, and Latin American countries [50]. The study was revised after two years by examining four key conditions to develop private sector mini-grids—licensing and legal provision, tariff regulation and cost recovery, expansion of the central grid, and access to finance - through an analysis of case studies from different countries to gather

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[3] As per RISE classification, green zone represents strong performers i.e. the top third, middle performers fall in the yellow zone, and red zone represent the weak performers i.e. the bottom third

insights on design elements of policy and regulatory measures for mini-grids and their application to the sector.

The IRENA analysis found that, in all the studied cases, different policy and implementation 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. Many countries like Rwanda, Nigeria, Peru, and Tanzania have considered mini-grid based solutions, within the country energy plans and strategies, as a means expand electricity access. Rwanda's National Electrification Plan (2018–2024), for instance, clearly demarcates habitations that would be connected through grid electricity and standalone off-grid technologies and also spells out mitigation options with respect to the risk of grid expansion [61]. Peru's rural electrification master plan is updated every two years so as to take into consideration the changed ground conditions and accordingly adapt targets and plans. The mini-grid regulation of Nigeria, launched in 2017, has considered the lessons from other countries in West Africa, and framed the policy in consultations with different stakeholders. The regulation includes, among others, provisions for tariff setting and payment of compensation as and when main grid arrives. Similarly, Tanzania's "Small Power Producers Program", which has evolved over the years since its launch in 2008, aims to attract the private developers for setting up both stand-alone and grid-interconnected mini-grids [62]. While the first phase of the program is based on lessons from Thailand Small Power Producer Program, the subsequent generations has attempted to provide customised licensing facilities and tariff regulations depending on mini-grid capacity.

The same study also observes that, while in many cases (e.g. India and Cambodia) mini-grids were implemented with 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 Rwanda, Nigeria, Sierra Leone, and Tanzania have set installed capacity ceilings (for instance lower than 100 kWp), which either are license-exempt or they follow a simplified implementation process (e.g. only registration with appropriate authority is required) [62]. The licensing processes have also been standardised by several countries. Nigeria and Tanzania for instance provide templates for applications for licences or permits, exclusivity agreements, tripartite contracts among others.

In terms of technical regulations and standards aiming to ensure safe and reliable operation of mini-grids, a study by IRENA observes that quality infrastructure for such systems 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 mini-grids have to conform to their regulatory commission's electricity distribution code to get a permit. Similarly, the Bureau of Standards in Tanzania jointly with their regulatory agency, supported by international partners, established a quality standard protocol 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, proper management of waste from the mini-grid projects after they cease to operate for end of component's life is a major challenge affecting environmental sustainability. While renewable energy based mini and micro-grids are considered as environmentally benign, the manufacture as well as disposal of different components - from solar modules to inverters to cables and switchboards to storage – all have their own environmental footprints. The equipment may not work (for example due to absence of effective maintenance) and is often dumped in an improper manner, posing serious health risks and release of pollutants and waste generation. [63]. Proper end-of-life management is thus extremely important for ensuring sustainability of mini-grid solutions but is not well researched.

In summary, to attain the objective of "access to electricity for all by 2030", different reports suggest 40%-50% of all installed capacity will be from mini-grids [15, 64]. The World Bank suggests that kWh generation cost of electricity from mini-grids is expected to reduce by two-thirds and that minigrids could provide electricity to 490 million people by the year 2030, for which nearly 210,000 mini-grids may have to be set up at an total investment of US $220 billion [64]. To achieve this, a favourable governance arrangement, regulatory environment and adequate incentives and subsidies are required to provide a level playing field. Further, successful implementation of mini-grid projects could be ensured by considering communities' exact needs and aspirations and dependable actual and future demand data. Moreover, as an alternative to the binary view of grid electricity systems and centralised service delivery or distributed generation and decentralised model of services, a more prudent approach might be 'complementary convergence' of both central grid and distributed technology solutions as well as service delivery models, learning from each other's strengths both technically and institutionally [65]. Finally, quality standards, system performance benchmarks and certification modalities are also needed to guarantee the quality of implementation and safe operation of off-grid and mini-grid solutions.

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

There are two ways by which off-grid electricity can be served - (i) standalone product-based solutions that is almost similar to a consumer durable product and (ii) community or collective network-based solutions like a solar mini-grid [66, 67]. Whether central grid or mini-grids, they are like any other business and must be commercially attractive and their viability often depends on well-designed tariff regulations. In principle, revenues from the grid or mini-grids need to take care of their capex and opex. In addition to affordability of connections, steady revenues necessitate realistic estimates of electricity demand as well as rational electricity prices for residential, commercial and institutional consumers. While average retail tariff and design of the minigrid projects may be impacted by subsidies, if any, the subsidies should be as high as necessary to ensure project viability while not impacting the government finances. Tariff schemes can be differently adopted, ranging from flat-rate to electricity prices based on levelised cost of generation or from load-based to electricity services-based, as well as from regressive to progressive electricity prices. Project economics impacts majorly the viability of main grid as well as mini-grid projects.

A study from India shows that the usual generation cost from decentralized generation is approximately INR[4] 23 – 33 (US$ 0.31 – 0.47) per kWh, depending on generation type [68] against average rural household spending of around INR 11/kWh (~US$ 0.16/kWh) to meet different loads - lights, mobile phone charging, appliances among others [69]. Another study from Bangladesh indicates that the levelised unit cost of electricity for solar home lighting systems and hybrid mini-grid projects (PV-diesel) ranges between US $0.344 per kWh and US $0.715 per kWh for the users [70]. On the other hand, the typical regulated grid tariffs are much lower than the typical tariffs for mini-grids, as there is a cross-subsidy element in most cases. For example, the grid tariff is approximately 120 XOF[5] (US$ 0.20) per kWh for central grid in case of Senegal versus more than 500 XOF (US$ 0.85) per kWh charged by private mini-grids [53]. Similarly, in India, private mini-grid developers charge between INR 25 (US$ 0.36) and INR 45 (US$ 0.64) per kWh (fixed + variable costs) against the average retail tariff of INR 3.95 (US$ 0.06) to INR 5.81 (US$ 0.08) per kWh for centralised grid depending on the states [71]. 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 [72]. For consumers, especially low-income consumers in remote rural areas, whether electricity is 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 PV projects when strategically located might produce generation-cost ratios to a minimum of US $0.042/kWh and are comparable with hydel generation-cost ratios of US $0.02 to US $0.03 per kWh. The same study also indicates that a fully decentralised generation approach (whether off- or on-grid) is not economically viable, with electricity prices almost 6 -12 times costlier as compared to the prevailing tariff. However, a combination of centralised (70%) and decentralised (30%) systems was found to provide affordable power, as well as to enable quicker implementation [73]. Another study from Uttar Pradesh, India observes that low capacity mini-grids may not be a viable design to attract private investments, if the existing feed-in-tariff in the state is considered, and other means of support such as capex support or soft financing or results based aid to reduce the levelised cost are not provided [74]. Medium to large-scale solar PV projects or sub-MW capacity mini-grids, on the other hand, might be a better proposition with competitive tariff because of economy of scale and scope and higher operational efficiency. Thus, to be financially viable, a mini-grid model has to be based on an

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[4] 1 US dollar = INR 70.

[5] 1 US dollar = XOF 590.

optimum (often-large) number of consumers. However, this raises a crucial issue for the private developers: are there enough locations in their target areas to set up mini-grids so as to have optimum number of consumers that is essential to run a commercial mini-grid business?

Generating adequate revenue in rural settlements to run operation is also more difficult as compared to urban habitations because of the consumers' lower ability to pay and lower demand. In some cases, households in rural areas are unable to make payment reflecting the full cost to provide electricity services [75]. Regulatory authorities, thus, have to set tariff for consumers, considering the affordability and power quality and at the same time ensuring that the private mini-grid operators can recover their costs and sustainably run the systems. With cost of electricity generation in case of mini-grids usually higher than for central grid, viability gap funding often becomes necessary wherever there is nationally harmonized tariffs. Thus, a uniform tariff structure should be accompanied by well-defined plans for subsidizing 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 mini-grid consumers at a harmonised national tariff to keep the consumer tariff low [72]. 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, regulatory authorities permit mini-grid project developers to fix tariffs in negotiation with electricity users such that prices are high enough to meet all costs but at the same time in line with the consumers' willingness and ability to make payment. Increasingly, regulatory authorities are taking a tailor-made ways to set mini-grid tariffs. Countries like Rwanda, Nigeria, and Tanzania, for example, allow such deregulated tariffs with some cap with respect to minigrid capacity (e.g. mini-grids with less than 100 kWp in Tanzania). In India, Electricity Act of 2003 allows mini-grid developers to enter into negotiated tariff with their consumers without the interference of the regulators [67]. Larger capacity projects are also need to follow standardized tools for electricity tariff computation (for instance multi-year tariff framework in Nigeria) and the tariffs also needs concurrence from the regulator. Indonesia and Peru have introduced such a method to standardize the tariffs and encourage participation by private developers [50].

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 [50, 76]. 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 [76]. Another associate risk is that local financial institutions may often not be familiar with decentralised renewable energy or mini-grids, and they many a times do not have the capacity to assess risks associated with decentralised projects. This is complicated by the fact that renewable energy resources vary from place to place and village to village and often these projects need customized design depending on populations and local electricity demand. Further, they also offer little collateral because the transaction cost to retrieve may be high and/or they may have limited value when shifted from the place of their original installation location

[77]. Bhattacharyya observes that the yearly estimates for energy access financing vary from US $11 billion to US $120 billion with a median value of US $50–60 billion for the next two decades [78]. He further opines that financing options - both downstream and upstream - would play a major role to expand off-grid provisions. Some agencies also observe that the enormity of the challenge is so big (especially considering that a large majority of the un-served population are at a socio-economic disadvantage living in rural and remote regions) that both low cost public as well private funding would be required [79, 80], Such a model of financing will ensure electricity services to the most vulnerable and marginalised communities. Thus, many countries are trying to get both public and private capital to scale-up mini-grid project implementation [81]. Finding the right model to finance mini-grids, managing government investments in the sector, getting long-term private co-financing, providing public support via subsidy or result-based aid, and the sustainable and well-organised operation of the systems are complex and demanding tasks: a right balance must be worked out to ensure their viability and sustainability as well as equity and fairness while providing electricity services.

5.3 Risks, uncertainties, and mitigation

Addressing the uncertainties around the expansion of the central grid is critical to mini/micro-grid projects' sustainability in any country. Well-defined rules of inter-connection and/or compensation instruments can reduce many of the risks. Many countries like Cambodia, Indonesia, Nigeria, Rwanda, and Tanzania, as well as few provinces from India, have developed regulatory frameworks that permit mini-grid project developers to move or dispose the assets (including selling full or part of the assets to the main grid electric utility), or become a small-scale generating unit to feed electricity to the main grid and/or become a distributor/franchisee by buying energy from grid utility for retailing it to consumers [50]. However, success of such arrangement is critical on the setting up of a viable tariff after interconnection. If a compensation instrument is made obligatory, it gives an exit option to mini-grid project developers. In such a case, the method to determine the compensation (for instance asset depreciation) is crucial. Access to a compensation option may also help to negotiate a just tariff that allows the mini-grid developer to cover both electricity sales and purchases to and from the central grid. For instance, Tanzania allows five years for compensation and covers only distribution assets, thus leaving substantial risks with the private project developers of mini-grids. An important point to highlight here is that users of renewable energy technologies most often compare the electricity prices with that of centralized grid and are thus likely to consider they are buying costly power. However, the mini-grid projects currently do not get the benefit to cross-subsidize their tariff like most grid operators in many countries. Thus the mini-grid sector will be ready to develop at a faster rate only when they start to offer improved and niche services at or below the monthly expenses on kerosene or paraffin used by un-electrified households or at prices similar to that of the regulated prices offered by main grid.

6. Conclusions and 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.

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 program involves several steps (such as prioritization and identification of investment projects, detailed design of projects, project implementation, and project monitoring and evaluation), and an appropriate organizational arrangement is essential for access program implementation.

The literature on governance arrangements for universal electricity access suggests there is no single template for successful implementation of such a program, but a strong leadership and a supportive environment is essential. While many countries have progressed 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. 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 electricity options is perhaps needed to reach a wider section of the population quickly, but such an approach has not yet been effectively implemented. More importantly, achieving access to electricity for all by 2030 would need large-scale implementation of electrification programs at the national level that will include grid extension and accelerated delivery of decentralised solutions.

Following from the above, a few areas for further research can be highlighted. The issue of co-existence of grid and renewable energy based off-grid solutions and their interactions in the long-term remains a possible area of further investigation, particularly in view of decarbonization and decentralisation of the electricity sector. Similarly, whether technological developments will lead to disruptive business models both in urban and rural areas remains to be seen. There is also need for further work in this area to investigate the design, feasibility, and organizational arrangement required to support programmatic delivery options.

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 central grid supply. This brings forth the issues of fairness, equity, and justice. An alternative option has been suggested where relatively large-scale renewable energy capacity could be embedded at the distribution network level [74]. The advantage here is the ability to capture scale and scope economy that reduces cost as the capacity can be procured in bulk. An alternative approach could also be to rely on bundling of projects over a larger geographical area (or spatial bundling). Studies of island-level electrification and the power supply to remote areas in Bangladesh have adopted such a spatial approach. Further research would be required in this field.

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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 and others [82]	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	PK Rs 5.51/kWh	Grid supply @PK Rs 10.35/kWh more expensive
2	Fodhil and others [83]	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 [84]	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 and others [85]	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 and others [86]	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 and others [87]	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 and others [88]	Health care facilities in Nigeria	PV/wind/diesel/battery or PV/diesel/battery hybrid systems	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

			depending on sites				
8	Nnaji and others [89]	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	Analyzed different communities with own load characteristics
9	Muh and Tabet [90]	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 optimization
10	Gebrehiwot and others [91]	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	Amutha and Rajini [92]	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, street lights, etc., and for a Base Trans-receiver Station (BTS)	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/kW h	Considered seven alternative technology options for optimization
12	Micangeli and others [93]	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 Bhattacharyya [94]	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 and others [95]	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: Compiled by the Authors.

Table A2: Selected Network Planner studies

ID	Author	Country case	Optimal solution			Investment need	Comment
			Grid %	Diesel mini-grid %	Standalone %		
1	Ohiare [30]	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 and others [96]	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 [97]	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 and others [98]	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 and others [37]	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 and others [99]	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 [47]	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: Compiled by the 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 and others [100]	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 and others [32]	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 and others [38]	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 and others [102]	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 and others [103]	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 and others [101]	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 [104]	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

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 [34]	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 and others [33]; Ciller and others [105]	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 [36]	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	González-García and others [106]	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	Mwalenga and others [39]	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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