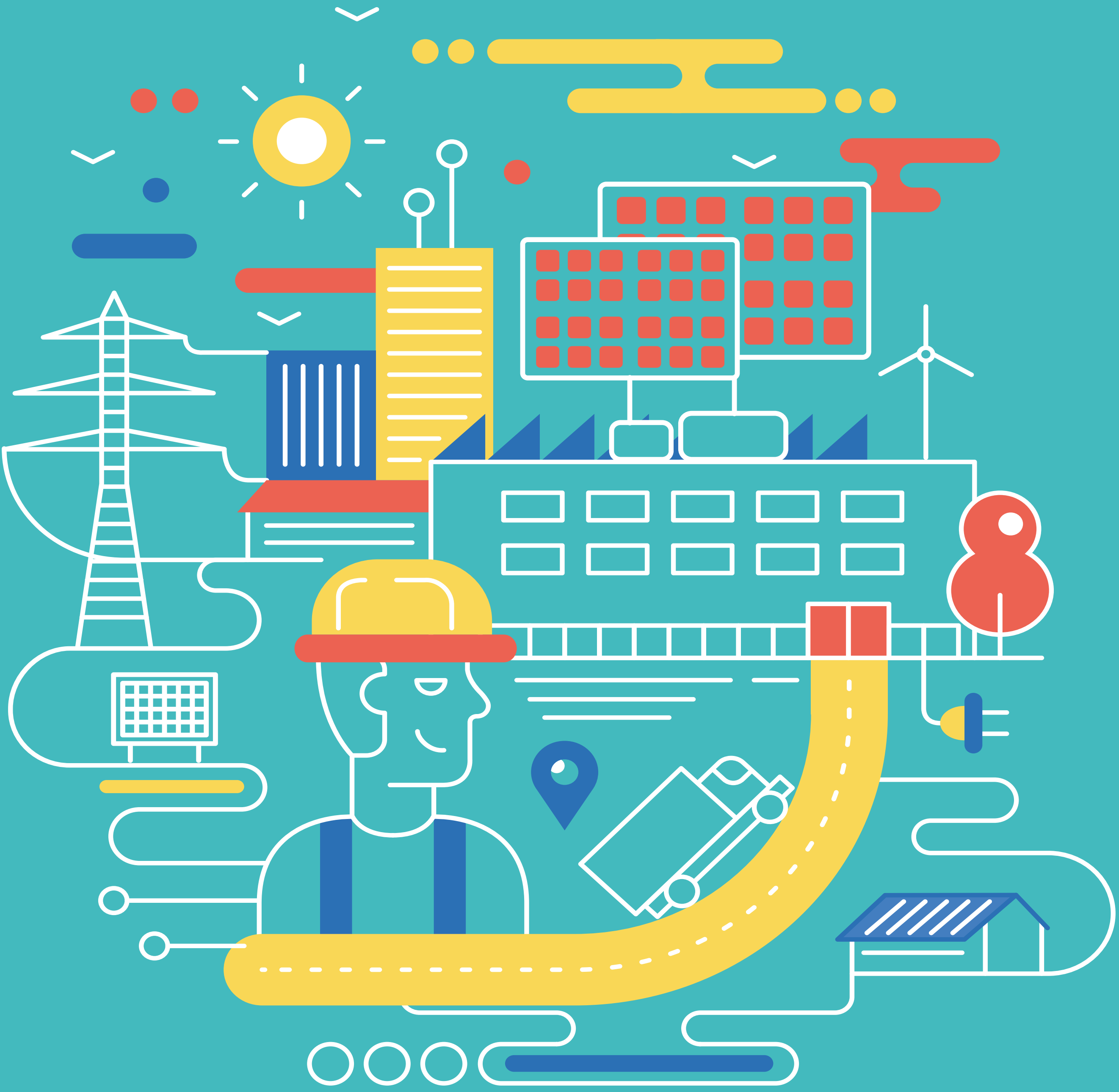
THE ROLE OF MINI-GRIDS FOR ELECTRICITY ACCESS AND CLIMATE CHANGE MITIGATION IN INDIA



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DOI:
https://doi.org/10.25561/94889

ACKNOWLEDGEMENTS

This report builds on research carried out within the UK-India Joint Virtual Clean Energy Centre (JVCEC), within which, the UK partners have received funding from the Engineering & Physical Sciences Research Council (EPSRC) for a project entitled "Joint UK-India Clean Energy Centre (JUICE)" with grant reference EP/P003605/1, and the India partners have received funding from the Government of India's Department of Science and Technology (DST) for projects entitled "India-UK Centre for Education and Research in Clean Energy (IUCERCE)" and "UK India Clean Energy Research Institute (UKICERI)". The views expressed in this report are those of the authors, and do not necessarily reflect the views of all JVCEC collaborators or of the funding bodies.

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Published: February 2022

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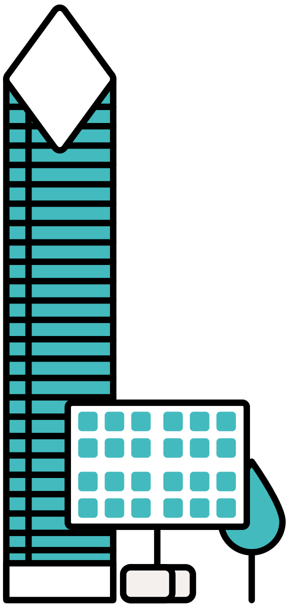
GLOSSARY

AC	Alternating current
Anchor load	Large, reliable uses of electricity such as agricultural facilities or health centres
c-Si	Crystalline silicon
CAPEX	Capital expenditure, for example mini-grid equipment such as solar panels
CdTe	Cadmium telluride
CEEW	Council on Energy, Environment and Water
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
Community uses of electricity	The use of modern electricity for the provision of key community services, such as for healthcare and education
DC	Direct current
DISCOM	Distribution company
Domestic uses of electricity	The use of electricity for services in the home such as lighting, phone charging, entertainment and domestic appliances
DR	Demand response
DSSC	Dye-sensitised solar cells
ESMAP	Energy Sector Management Assistance Program
gCO_{2eq}	Grams of carbon dioxide equivalent
GHG	Greenhouse gas
GST	Goods and Services Tax
GW	Gigawatt
Hydel	Hydroelectric
ICT	Information and communication technologies
IEA	International Energy Agency
INR	Indian Rupee
JNNSM	Jawaharlal Nehru National Solar Mission
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Kilowatt-peak, a measure of solar capacity
LCA	Life cycle analysis
LCOE	Levelised cost of electricity ($/kWh)
LCOS	Levelised cost of storage (c/kWh/cycle)
LCUE	Levelised cost of used electricity ($/kWh)
LED	Light-emitting diode
LFP	Lithium Iron Phosphate
LTO	Lithium Titanate Oxide
LV	Low voltage
m-Si	Monocrystalline silicon
MAC	Marginal abatement cost ($\$/CO_{2eq}$)
Mini-grid	An electric power generation and distribution system which provides power to multiple users
Multi-Tier Framework (MTF)	A framework for classifying levels (Tiers) of electricity access based on the several performance criteria
MW	Megawatt
MWh	Megawatt-hour
NCA	Nickel Manganese Aluminium Oxide
NEP	National Electricity Plan
NGO	Non-governmental organisation
NMC	Nickel Manganese Cobalt Oxide
O&M	Operations and maintenance
Off-grid solution	An electricity system which operates independently of the national grid network
OPEX	Operational expenditure, for example maintenance fees or fuel costs
OPV	Organic photovoltaics
p-Si	Polycrystalline silicon
PAT Scheme	Perform, Achieve, Trade Scheme
Productive uses of electricity	The use of modern electricity services to reduce drudgery, contribute to economic activities, or facilitate business operations
PV	Photovoltaic
R&D	Research and development
REC	Rural electricity cooperative
Saubhagya Scheme	Policy to provide last mile connectivity to unelectrified households
SHS	Solar home system
SME	Small or medium enterprise
Sustainable Development Goal 7 (SDG 7)	The goal of ensuring access to affordable, reliable, sustainable and modern energy for all
T&D	Transmission and distribution
tCO_{2eq}	Tonnes of carbon dioxide equivalent
TW	Terawatt
VEC	Village energy committee
W	Watt
Wp	Watt-peak, a measure of solar capacity

EXECUTIVE SUMMARY

Sustainable Development Goal 7 aims to achieve access to sustainable, affordable, reliable, and modern energy for all. Access to electricity is critical for development and economic growth and can support productive livelihoods and power critical community services such as for healthcare and education. Solar mini-grids can offer the most cost-effective option for rural and remote communities not yet connected to the grid and can deliver reliable, high-quality power which is able to serve multiple uses and meet growing demand over time.



India has implemented a series of policies which have rapidly increased the number of connections throughout the country. Whilst almost all communities are considered "electrified" by the Government of India, the proportion of households within those communities with grid connections varies greatly within and between states. Whilst grid electricity is cheap for customers which have access, it is also carbon-intensive and can be unreliable. Around 1,800 mini-grids have been installed in the country by 2019 and, whilst many policy and regulatory challenges remain, these systems can be a cost-effective and low-carbon option for last mile electrification in India.

Designing effective solar mini-grids requires an understanding of their technical performance as well as their economic and environmental impacts. Computational modelling can evaluate a variety of potential system configurations, and their ability to meet different community demands, to identify those with the lowest costs and greenhouse gas emissions before these systems are deployed. Falling prices and technological improvements, both for solar and battery storage, are expected to further drive down mini-grid costs. Maintaining long-term battery performance in rural environments will be critical in ensuring reliable and sustainable electricity services over many years.

The needs of a community, and therefore the electricity services that can support them, must be the central consideration when designing solar mini-grids. Electricity demand can be categorised into domestic, productive and community uses – each with their own characteristics and impacts on system design. Modelling techniques can evaluate the electricity requirements of newly-connected communities and estimate how this could grow over time as the community develops.

Deploying mini-grids in India offers an opportunity to provide electricity services to under-served communities but implementation challenges remain. The affordability of mini-grid tariffs for customers compared to the subsidised rates of the national grid, the financial and business models for mini-grid operators, and the community involvement, management and ownership each require further investigation to identify the most effective modes of implementation. Understanding these challenges will be critical in scaling up the potential for solar mini-grids to provide affordable, reliable, sustainable, and modern access to electricity services for rural communities in India.

CONTENTS

INTRODUCTION

Sustainable Development Goal 7 aims to achieve access to sustainable, affordable, reliable, and modern energy for all.

- Access to electricity is critical for human development and economic growth. Beside supporting domestic activities, it can facilitate productive uses of electricity and support community services, such as healthcare and education.
- Solar mini-grids can be the most cost-effective option to provide electricity to rural and remote communities not served by the grid. They can also be a more sustainable option than fossil fuel based grid electricity.
- Owing to their high capacity power compared to other off-grid solutions, solar mini-grids can support communities' socio-economic development by providing reliable and modern access to electricity services, and are able to serve multiple uses and growing demand over time..
- The number of people worldwide with mini-grid connections has grown from 9 million in 2016 to 47 million in 2019, with 490 million projected for 2030.

1.1. SDG7: SUSTAINABLE ENERGY ACCESS FOR ALL

The 2030 Agenda for Sustainable Development, launched in 2015, set out a comprehensive framework of targets and goals with the aim of eradicating poverty worldwide and ensuring long-term development and prosperity. Amongst its seventeen Sustainable Development Goals (SDGs), Sustainable Development Goal 7 (SDG 7) aims to ensure reliable, affordable, sustainable, and modern energy for all by 2030 and provides a worldwide political recognition of the importance of energy for development. SDG 7 has targets to increase the share of energy from renewables in the global energy mix, improve energy efficiency, and increase investments in sustainable energy infrastructure; its first target, however, is to ensure universal access to affordable, reliable, and modern energy services.

Access to energy is typically considered as being comprised of two components: access to electricity (for example for lighting, communications, appliances, or other uses) and access to cooking. Whilst the latter is a critical issue for the third of the world's population who rely on the most basic, and often dangerous, cooking systems (United Nations Statistical Division, 2021) in this report we focus on the former: the need to provide access to reliable, affordable, and sustainable electricity.

Worldwide access to electricity has been improving in the last decade, with the number of people without access to electricity dropping from 1150 million in 2010 to 770 million in 2019 (IEA, 2020b). Some countries, such as India, have made considerable progress in increasing the electricity access rate of their population, while others have seen less progress, such as Sub-Saharan African countries which hosted about 75% of the global population (571 million people) without access in 2019 (IEA, 2021a). Whilst access to electricity can be classified in terms of a binary description (having access or not), the Multi-Tier Framework (Bhatia and Angelou, 2015) offers a more detailed definition based on the availability of electricity services (see Box 1.1).

BOX 1.1: THE MULTI-TIER FRAMEWORK (MTF) AND ACCESS TO ELECTRICITY SERVICES

In 2015 the Energy Sector Management Assistance Program (ESMAP) at the World Bank provided a conceptual framework to redefine energy access, moving from a binary definition (connected or not) to one which encapsulates several dimensions of energy access (Bhatia and Angelou, 2015). The MTF can be applied to electricity access and to energy for cooking, across domestic, commercial and institutional settings, and highlights socio-economic development as the primary objective of expanding energy access. Moreover, the framework states how access to energy pertains to usability of supply rather than actual use of energy, particularly the potential to use the available energy supply when required for the applications that a user needs or wants. The Tiers of electricity access can be broadly stratified into representative levels of service (Bhatia and Angelou, 2015) and appliances (Tenenbaum *et al.*, 2014):

- Tier 0: no access to electricity sources
- Tier 1: task lighting and phone charging
- Tier 2: general lighting, television and fan
- Tier 3: Tier 2 + any medium power appliances (e.g. food processors, rice cookers and washing machines)
- Tier 4: Tier 3 + any high power appliances (e.g. refrigerators, irons, microwaves, carpentry tools)
- Tier 5: Tier 4 + any very-high power appliances (e.g. air conditioning, space heating, milling, electric cooking)

The higher Tiers of electricity access build upon the services of those that precede them, providing access to higher-power appliances and supporting greater opportunities for community and economic development.

SDG 7 stresses the importance of affordable, sustainable, reliable, and modern energy for all. As such the electricity provision should be:

- Low cost, so that even the poorest people in society can use it to fulfil their needs and desires;
- Low carbon, with low greenhouse gas (GHG) emissions and other environmental impacts to minimise contributions to climate change;
- Dependable and predictable, to allow people to use electricity services at their convenience;
- Modern, safe and efficient, to serve multiple end uses and to allow growing demand over time.

These criteria are critical in realising the benefits of SDG 7 for the hundreds of millions of people without access to electricity, and many more with unreliable access, and in supporting sustainable development and long-term prosperity.

Providing affordable, reliable, sustainable, and modern electricity services to rural communities, businesses, and public institutions encompasses a wide range of potential end uses. Technological advancements – particularly amongst renewable sources, driven by their improving performances and falling prices – have unlocked opportunities to provide power in rural areas via off-grid electricity systems, opening options for providing power to under- and unelectrified communities.

1.2. ENERGY ACCESS FOR COMMUNITIES' SOCIO-ECONOMIC DEVELOPMENT

Access to electricity is critical for human development and economic growth, especially in rural areas of developing countries where modern infrastructure and services have historically been lacking. About 80% of people without access to electricity live in rural areas and so most of the electrification effort is targeted toward rural electrification (IEA, 2021c).

Reliable electricity can improve the livelihoods of rural businesses and the resilience and self-reliance of rural communities. Modern electricity services, able to serve multiple end uses and increasing levels of local demand, can facilitate productive uses of power (supporting the local economy), community services (such as for healthcare and education) and wider socio-economic benefits (supporting long-term development).

“Productive uses of electricity” is used to refer to the use of modern electricity services to reduce drudgery, contribute to economic activities, or facilitate business operations. Improved access to electricity can foster agricultural development by increasing the productivity of farmland (for example by providing access to water pumping for irrigation) and by supporting storage of crops and agri-food products. It can increase productivity of commercial services and small and medium enterprises (SMEs) through extended operation hours, mechanisation, and preservation of products as well as enhanced communication. It can also enable the scale-up or growth of new income generating activities which, without access to power, would have been impossible.

“Community uses of electricity” is used to refer to applications which include powering infrastructure and provision of key community services, such as for healthcare and education. Electricity access enhances the quality of essential healthcare services but is currently lacking worldwide: only 41% of low- and middle-income country healthcare facilities have reliable electricity. Education facilities, which benefit from electricity access by providing lighting for longer hours of studying and access to ICT resources, experience even lower access rates: according to UNESCO estimates in 2017, only 35.1% of sub-Saharan African primary schools and 50.7% of those in Southern Asia had access to electricity (Sustainable Energy for All, 2019b). Many of these unelectrified public institutions are located in remote areas and characterized by poor surrounding infrastructure and low energy demand, making them unattractive to traditional energy service providers..

More generally improved electricity access has been found to have positive impacts on human and community development. It can improve food security through both direct impacts on agricultural production and indirect ones through income generation (Candelise, Saccone and Vallino, 2021). It can support gender balance and women empowerment by improving safety conditions (lighting can reduce risks of sexual and gender-based violence at night) and health levels (reduction in the use of kerosene lamps indoors), reducing the time spent on tasks typically the responsibility of women (such as fetching water) and creating opportunities to save time (such as water pumping) and generate income (women empowerment) (Bos, Chaplin and Mamun, 2018; Riva *et al.*, 2018; ESMAP, 2019).

Need for reliable and predictable electricity provision

Electricity access can deliver socio-economic development when reliable and modern electricity services, able to serve multiple end uses and increasing levels of demand over time, are provided. Indeed, access to electricity means not just availability of connection, but a dependable and predictable electricity supply which could serve multiple uses and support a growing demand over time.

An estimated 2.8 billion people who have access to electricity suffer limitations or instabilities which limit their use of electricity services or constrain their livelihoods (The Rockfeller Foundation, 2020). Using an electricity consumption of 1,000 kWh per person per year as a threshold, estimated to be the level at which a country achieves middle-income status, would leave approximately 3.6 billion people currently living in energy poverty (The Rockfeller Foundation, 2020). By considering connections which offer fewer than 12 hours of downtime per month as reliable, analysis of the World Bank Enterprise Surveys suggests more than 1.4 billion people have unreliable access to electricity – as a conservative estimate – in addition to those without any access at all (Sustainable Energy for All and The Rockfeller Foundation, 2020).

It is therefore necessary to categorise electricity access not just in terms of whether or not a connection is available – as these can vary greatly in terms of quality, reliability and usefulness – but also as a system which better captures the multifaceted nature of electricity access. The reliability of electricity provision is especially important for rural enterprises, for which a lack of reliable power could limit their productivity, income, or ability to do business. Agricultural activities such as milling, egg incubation and refrigeration for food products also offer opportunities for improved productivity but each rely on the consistent availability of power (Power for All, 2020). Figure 1.1 shows that India particularly stands out as case of study when considering reliability as an essential attribute to electricity access (see also Section 2.2). The Indian national government has stated that 99.99% of communities are connected to the national grid network (Indian Ministry of Power, 2021), but rural areas of north-central states receive an average of only 18.5 hours per day, with two thirds of households facing outages at least once per day (Agrawal *et al.*, 2020).

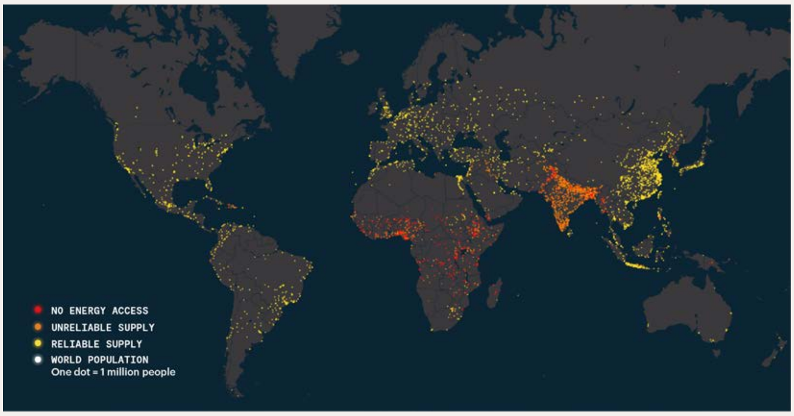


Figure 1.1. The distribution of an estimated 1.4 billion people who have unreliable energy access (orange circles), from the Electrifying Economies Project (Sustainable Energy for All and The Rockfeller Foundation, 2020).

BOX 1.2: IMPACT OF COVID-19 ON ENERGY ACCESS

The Covid-19 pandemic has slowed global progress in access to electricity, reverting the trend of the last decade. As shown in Figure 1.2, both new grid and off-grid connections stalled and, owing to population growth especially in Sub-Saharan Africa, resulted in the number of people without access increasing by 2% in 2021 (Cozzi, Tonolo and Wetzel, 2021).

The slowdown significantly affected stand-alone off-grid solutions, which declined more than 20% in 2020 (Cozzi, Tonolo and Wetzel, 2021). Travel limitations have prevented installers from reaching households, particularly in more remote areas, and supply chain disruptions created system components delays and price increases.

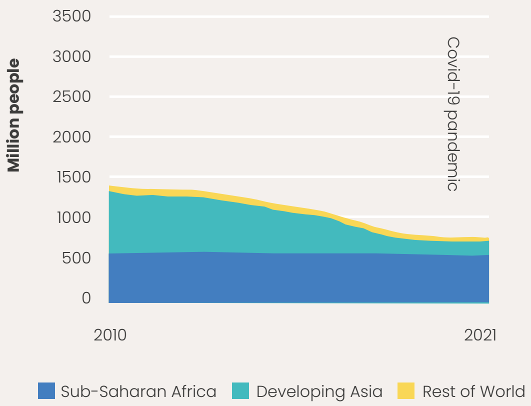


Figure 1.2. **The number of people without electricity access in Sub-Saharan Africa, Developing Asia, and the Rest of the World** (Cozzi, Tonolo and Wetzel, 2021).

Moreover, the pandemic has reduced households' ability to pay for energy services, resulting in new off-grid systems installations skewed toward small scale installations (i.e. a solar home system instead of larger mini-grids), thus not community level end-uses. Acknowledging this, the IEA advises governments and donors to put energy access at the heart of recovery plans and programmes to avoid such a reversal of recent progress (IEA, 2021c). The post-Covid-19 recovery (see Box 1.2) should target both access to reliable electricity and climate change challenges, and the investments made over the coming years will determine the ability of the global energy system to address them (The Rockfeller Foundation, 2020).

1.3. ELECTRIFICATION OPTIONS

Providing reliable and sustainable electricity access requires appropriate technologies, in addition to careful planning and supportive policies. Three main options, shown in Figure 1.3, have emerged as viable options for electrification:

- Extension of the national grid, typically branched from the main network;
- Solar lanterns and home systems (SHSs), designed for single households;
- Mini-grids, for community-scale electrification.

Each technological option has its advantages and drawbacks. The potential suitability of each is determined by many factors including costs, environmental impacts and ultimately its potential to meet the needs and desires of its specific end users in the long term.

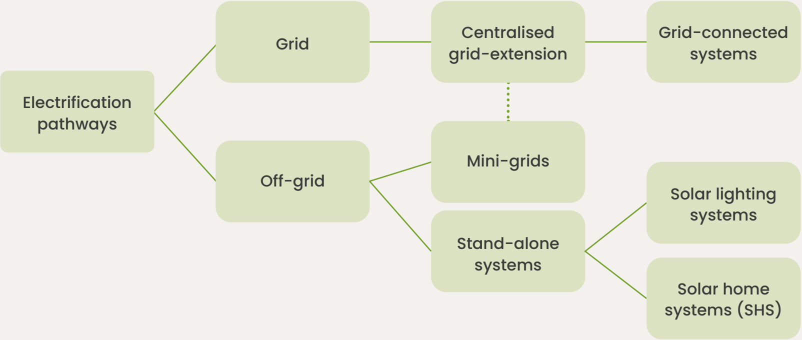


Figure 1.3. **A summary of the typologies of rural electrification pathways, from** Ortega-Arriaga *et al.* (2021).

Grid extension

Extension of the national grid network, from the existing centralised network into new areas, has been the traditional and predominant electrification approach in both developed and developing countries. Between 2000 and 2016, around 600 million people gained access via grid extension (IEA, 2017). Grid extension can provide reliable, high-capacity electricity to serve a wide range of electricity needs at the household level as well as for businesses, industry and community services with the highest power demands. Centralised networks generally have the greatest resilience against unexpected increases in demand and, owing to their access to a range of large-scale renewable and dispatchable generation sources, can supply power reliably throughout the year.

The advantages of grid electrification are predicated, however, on the nature of the current network. Grid extension inherently locks in the newly-connected community to the potentially carbon-intensive energy mix of the present network. Furthermore, Bos, Chaplin and Mamum (2018) found that in countries or regions in which electricity demand outweighs supply – resulting in load shedding or blackouts – connecting new communities to the grid network without an appropriate increase in generation can exacerbate existing problems, with rural areas often being the first to experience shortfalls in electricity provision.

Bos, Chaplin and Mamum (2018) also found that the capital investments required to build and maintain complex infrastructure can be very high and that grid extension over large distances to communities with little or no current electricity demand is generally not economically viable, as this would result in high generation costs per kWh provided. However, once the grid infrastructure is in place, electricity provided to the final user by the grid could be the cheapest option, particularly in presence of subsidised electricity tariffs (as for example in India - see Section 2.3).

Solar lanterns and solar home systems

Technological innovations and falling prices have led to options for decentralised rural electrification via smaller systems which operate independently of the national grid network. Solar lanterns – small, integrated units of a solar panel, battery, LED light and often phone charging port – can provide simple lighting and electricity services, usually Tier 1 of the MTF (less than 50 W of power available for less than four hours per day (Bhatia and Angelou, 2015)), and have been the most commonly-used technology globally for basic electrification by volume of sales (IRENA, 2018). Whilst these can be a valuable stepping-stone as a replacement for traditional sources of lighting such as candles or kerosene lamps, they typically cannot support higher-power services required to support long-term development goals.

Solar home systems (SHS), meanwhile, have emerged as a viable method of providing reliable electricity services to single households or businesses. These systems are larger than solar lanterns and are typically composed of a solar panel, battery, electronic control components and wiring. They often come packaged with other appliances, such as a few LED lights and phone chargers, and SHSs can usually support other appliances, such as radios and televisions. Larger SHSs can also support refrigerators or some productive uses of electricity, which can reach Tier 2 or Tier 3 of the MTF (50-800 W of power available for up to 16 hours per day (Bhatia and Angelou, 2015)).

A SHS can be used anywhere that there is sufficient solar resource to provide power: as a result, households in rural and remote communities no longer need to wait for large grid-focused infrastructure projects to reach their communities, but instead can procure systems for themselves. The private sector has capitalised on this opportunity and companies have developed business models ranging from direct sales (selling SHSs outright to consumers) to contract-based models (usually a lower down payment by the customer, followed by recurring payments for continued access to the electricity services). The prevalence of mobile money, especially in Africa, has facilitated the latter model, whilst remote monitoring and control – allowing companies to shut down systems – can force customers to keep up with their payments. In the first six months of 2021, 2.1 million solar lanterns and 1.3 million SHS were sold worldwide – a total capacity of 34.1 megawatts (MW) – and an estimated 360 million people have received access to electricity via these means since 2010 (Global Off-Grid Lighting Association, 2021).

Solar lanterns and SHS have seen a huge increase in usage but nonetheless suffer challenges to providing electricity access. The power capacities of typical systems limit users to domestic services such as lighting, phone charging and entertainment, whilst productive uses for machinery, agriculture processing and higher-power demands are usually out of reach. Institutional users such as schools and healthcare facilities could avail the advantages of larger SHSs, but computers or critical health equipment would likely require still larger electricity systems to provide higher-capacity power and for longer durations. The manufacturing quality of these devices, meanwhile, can vary greatly and low-quality units which quickly break can cause market spoilage for their higher-quality, and typically more expensive, counterparts which are reliable enough offer long-term electricity access. Finally, SHS can meet the needs of single household but, for entire communities without electricity access, those without the ability to pay will be left behind. To provide affordable, reliable, sustainable and modern electricity to entire communities – as well as with sufficient capacities to support productive and institutional uses of electricity – another approach will be needed.

Solar mini-grids

Solar mini-grids, the focal technology of this work, can offer a source of affordable, sustainable, reliable, and modern electricity to entire communities. Specific definitions of what makes a “mini-grid” (also stylised as “minigrid”) vary and so we use that of the World Bank, in that a mini-grid is an electric power generation and distribution system which provides power to multiple users

(ESMAP, 2019). Systems which have been described under other nomenclature, for example "micro-grid" or "nano-grid" usually relating to their capacity, can be included under this term, with more than 99% of mini-grid systems worldwide having installed capacities of a few kilowatts (kW) to several megawatts (MW) (ESMAP, 2019).

Solar mini-grids typically operate independently of the national grid network and so can be used in rural and remote areas. They are usually composed of a solar array (made up of many panels), battery banks for energy storage, electronic control units to monitor performance and measure customer usage, and a distribution network to transmit power from its generation location to the homes, businesses, and institutions in the local community, such as a village (SE for All and Bloomberg NEF, 2020a). The composition and a description of the relevant technologies and components is given in Section 4.

Owing to their increased electricity generation capacity, solar mini-grids offer a range of design options (see Section 3) to meet a wide variety of community services (see Section 5). Depending on the goals of the implementing organisation – which could be a government agency, a private company, a non-governmental organisation (NGO) or even the community itself – a mini-grid can provide basic electricity services, aligned to Tier 1 or 2 of the MTF, or reliable high-capacity power for businesses and institutions, aligned to Tier 4 or 5. These can bring a range of socio-economic benefits (see Section 6) as demand for electricity services grows, along with first access to electricity for a community (Few *et al.*, 2022).

Solar mini-grids are not without their drawbacks, however. The larger capital requirements for the initial system set-up can be prohibitively expensive to private mini-grid development companies and generally require long-term investments to be paid off over time (Okapi Research and Advisory, 2017). Uncertainties around community uptake of the services being offered, their ability to pay, and the threat of national grid expansion – potentially providing cheaper electricity tariffs for the consumer, undercutting the mini-grid's tariffs – can make this investment riskier (Okapi Research and Advisory, 2017). As with all electricity systems they require dedicated operation and maintenance but, if located in more rural areas, the expertise can be difficult to source locally or expensive to provide regularly (Power for All, 2019). Despite these challenges, solar mini-grids are expected to be a major enabler in achieving SDG7 by 2030 (ESMAP, 2019).

The growth in mini-grid deployment has been significant: more than 19,000 mini-grids have been installed across 134 countries, providing electricity access to 47 million people (ESMAP, 2019). As shown in Figure 1.4 60% of mini-grid projects worldwide have been implemented in Asia, whilst solar is the dominant generation technology with 50% of mini-grids using it as the power source – more than double the next most common technology (Sustainable Energy

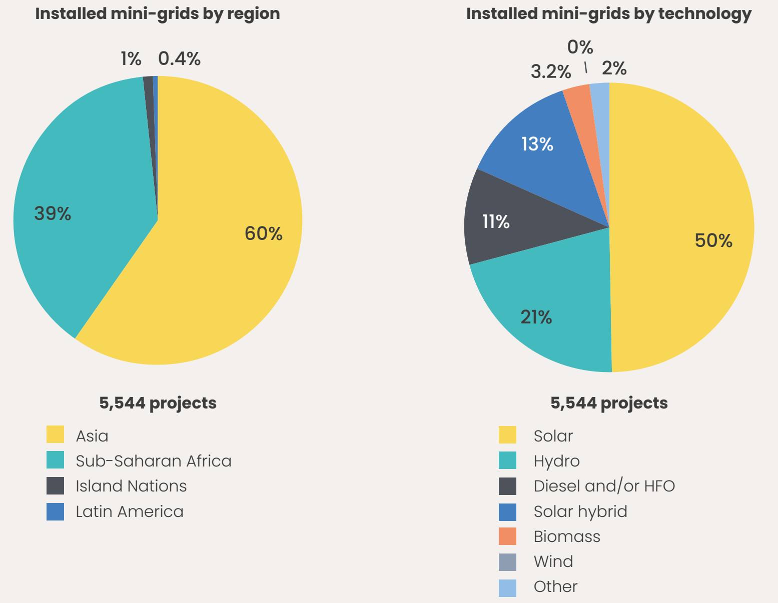


Figure 1.4. **The global distribution of mini-grids by region and categorised by technology, from** Sustainable Energy for All and Bloomberg NEF (2020b).

for All and Bloomberg NEF, 2020b). Solar power is expected to be the prominent technology for mini-grids in the future, which as a whole are projected to provide electricity access for 490 million people through 210,000 systems by 2030 (ESMAP, 2019). Better understanding of solar mini-grids can help governments, the private sector, academia, and others to fulfil these expectations and provide sustainable electricity access to all.

Options for affordable and sustainable electricity access

Choosing the optimal electrification solution requires consideration of several factors, including the costs of the system and the cost of the electricity provided to the final user, its overall environmental impact as well as its suitability to serve specific end uses and support communities' socio-economic development. Recalling SDG 7 definition, an optimal electricity provision should be affordable, sustainable, reliable and modern.

Investing in the least cost option for electrification, i.e. the one with lowest generation cost per kWh provided , is the first step to guarantee higher affordability of electricity provision. However, the affordability of electricity provision, i.e. the cost for the final user, would depend not only on the generation cost of the technology and system chosen, but also on the supply tariff charged, which itself would depend on markets and policy factors (see also Section 6). In India for example grid electricity is highly subsidised, making it the cheapest option where the grid is available (see Section 2.3).

Comparing costs of different electrification options, in particular grid extension versus cost of off grid solutions, poses its challenges, due to both the variability of the costs themselves and the different metrics often used in the available estimates (see Figure 1.5). Some estimates report the generation cost only, others also include levelised unit cost of transmission and distribution, and in some cases tariffs charged are used as proxy of grid electricity cost (which in case of subsidised tariffs would make the grid more competitive). Overall, the costs of electricity provided by off-grid systems has been reported to range around $0.2–1.4/kWh, compared to a range of below $0.1/kWh to more than $8/kWh for grid access. These ranges highlight how off grid solutions in given circumstances are already a more cost-effective option compared to grid extension (Ortega-Arriaga et al., 2021).

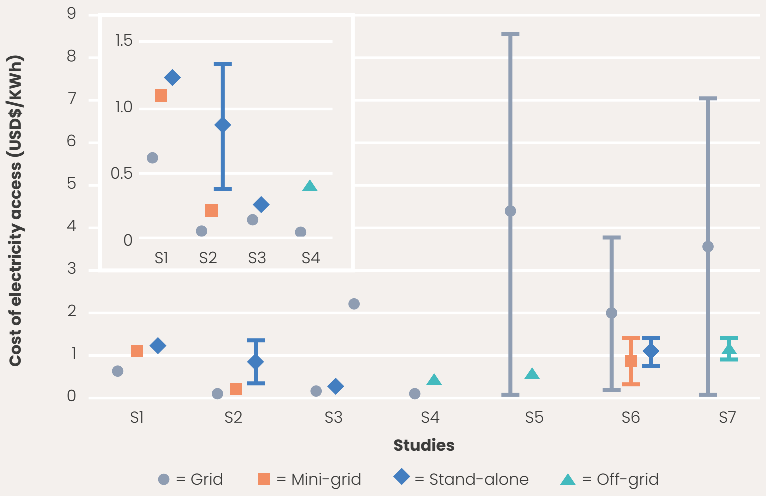


Figure 1.5. **Evidence of costs from different electrification strategies in USD2018. The circle in the middle of the whisker plot represents the midpoint of each range. Depending on the study, the cost of electricity access was calculated using different metrics (e.g. LCOE and LCC). From** Ortega-Arriaga *et al.* (2021).

The costs of off-grid solutions vary according to the technology used, the local resource availability and other operating factors (including e.g. accounting for diesel fuel costs for hybrid system configurations). Metrics and assessment of mini-grid costs are further discussed in Section 3. Grid extension investments instead can vary depending on the electricity mix of the centralised generation (and the relative costs of different electricity sources), on the distances between load centre and final point, the local demand to be served, and the type of grid infrastructure that needs to be developed (Ortega-Arriaga et al., 2021). They tend to increase with longer distances, longer distribution lines and associated higher electrical transmission and distribution (T&D) losses (Mahapatra and Dasappa, 2012). Evidence shows higher costs of grid extension than off-grid solutions in providing electricity access to more remote areas, due to LV (Low Voltage) line from last mile connectivity being a major component of T&D costs (Narula, Nagai and Pachauri, 2012). Thus, off-grid solutions tend to be more cost effective than grid extension for electricity provision to rural areas, which are more remote and characterized by sparsely populated communities (Mandelli *et al.*, 2016; Sustainable Energy for All, 2019a).

Goals to increase access to energy need also to be sustainable. Environmental impact of electrification is mainly assessed on terms of compatibility with commitments to address climate change and greenhouse gas (GHG) emissions (other environmental impacts have been scarcely investigated to date) (Ortega-Arriaga *et al.*, 2021). All electricity technologies inherently rely on electronic components and equipment which incur GHG emissions during their production, transport, and – in the case of non-renewable sources – usage. Even renewable technologies, such as solar panels, rely on energy-intensive manufacturing processes and each option for rural electrification, described more in the next section, has its own environmental impact.

Electrification via the national grid network typically incurs high GHG emissions. The emissions intensity of gas-fired power plants can be around 400 gCO_{2eq}/kWh, whilst coal power plants can be several times higher, in addition to the embedded emissions of the transmission infrastructure (IEA, 2021c). The emissions of off-grid solar technologies, however, can be much lower: 50-130 gCO_{2eq}/kWh over the lifetime of the systems, even including requirements for local infrastructure such as battery storage and distribution networks (IEA, 2021c; Ortega-Arriaga *et al.*, 2021). Furthermore off-grid lighting can offset GHGs from traditional lighting sources, such as candles or kerosene for lighting: an estimated 86 million tonnes of CO_{2eq} have been avoided by solar lanterns and SHS sold since 2010 (Global Off-Grid Lighting Association, 2021).

Overall, there is a growing consensus that relying on traditional means of electrification, and the high carbon impacts of national grid networks (albeit typically falling, as a result of utility-scale renewable projects), is neither environmentally sustainable nor necessarily the lowest-cost option for implementers for providing electricity access (The Rockfeller Foundation, 2020). Off-grid renewable based solutions have been increasingly used worldwide to provide electricity access (see Figure 1.6), in particular solar based solutions thanks to the remarkable cost reductions achieved by solar technologies over the last decade (see also Section 4). They have been projected by the International Energy Agency as the least-cost way to provide electricity access to more than half of the people who will gain access to electricity by 2030 (IEA, 2021c).

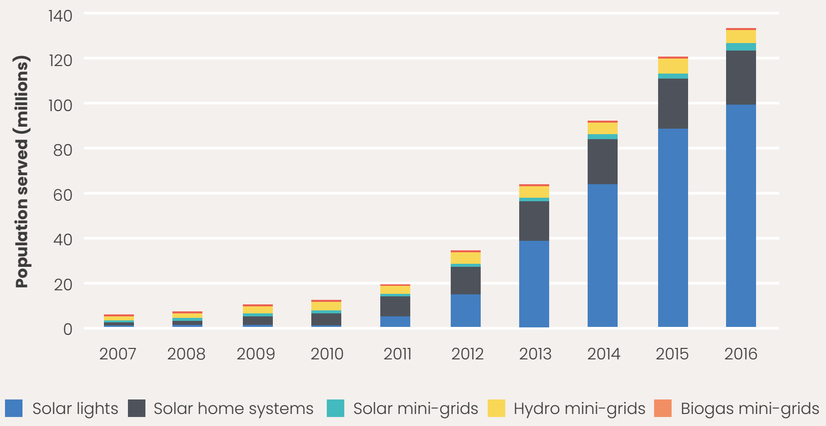


Figure 1.6. The number of people served by off-grid solutions globally From IRENA (2018)

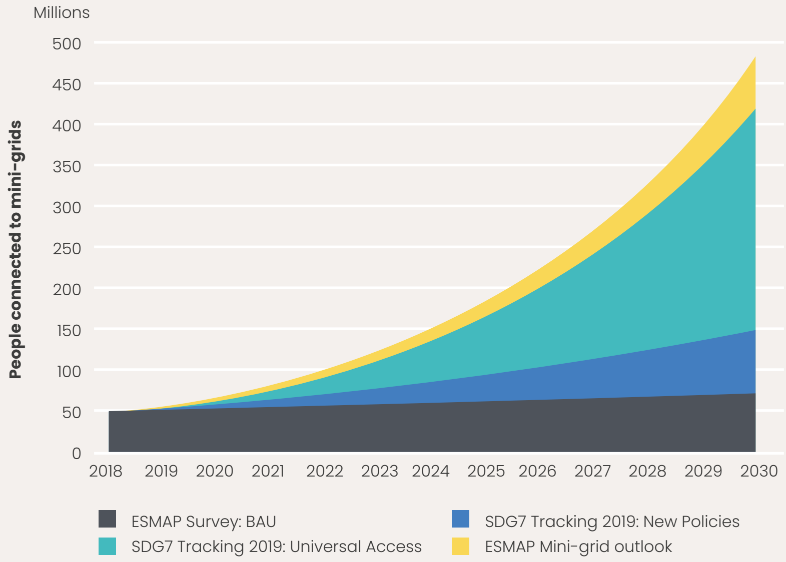


Figure 1.7. **The number of people projected to access electricity via mini-grids by 2030 under different deployment scenarios** (ESMAP, 2019).

1.4. THE ROLE OF MINI-GRIDS AND RATIONALE FOR THIS PAPER

Amongst off grid solutions, mini-grids are projected to play an important role in providing affordable, reliable, sustainable, and modern electricity services provision. The IEA estimated that by 2030 around 470 million people will access electricity via a connection to a mini-grid, a tenfold increase from 2019 (see Figure 1.7) (ESMAP, 2019). Solar-hybrid mini-grids are projected to account for the highest share of the future installed capacity (ESMAP, 2019), and this report will mainly discuss issues specific to mini-grid system implementation.

Solar mini-grids can provide cost-effective and sustainable electricity services to households, businesses and community institutions, in particular for the last mile connection of rural and remote communities (ESMAP, 2019). Compared to other off-grid renewable solutions they can support higher-capacity power usage, including in areas that centralised grid extension has so far failed to reach, thus supporting a growing demand over time and allowing a community to move along different Tiers of electricity access (see Box 1.1). Therefore, they offer the opportunity for reliable, community-scale electricity access to support improvement in quality of life and socio-economic development of communities.

In order to reach their potential, many issues around the most appropriate design, technologies, implementation models and desired impacts for solar mini-grids will need to be accounted for. We focus on how these challenges can be addressed in general, but also with specific application to India.

The report proceeds as follows:

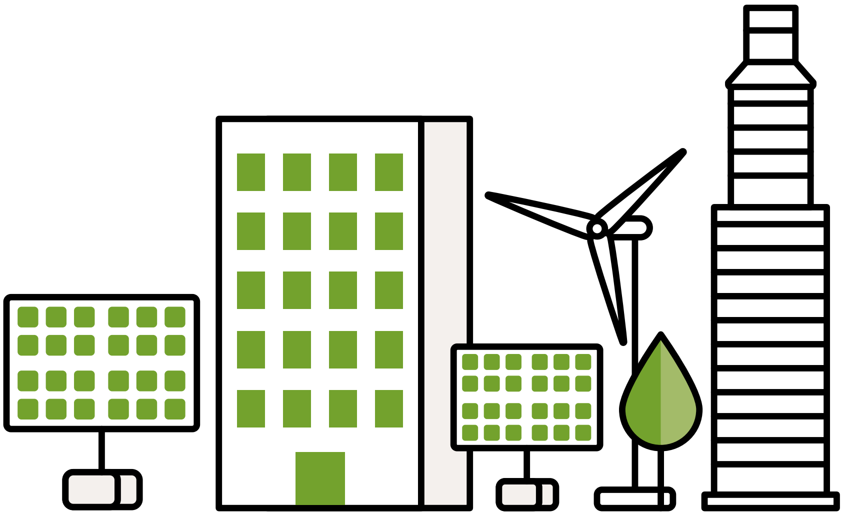
- Section 2 reviews the recent electrification situation and policies, and the status of mini-grid deployment, in India. Though the Government of India is moving forward with high goals for electricity access through different schemes, further reductions of GHG emissions and accelerated last mile electricity access are necessary. Solar mini-grids will be pivotal in achieving the low carbon last mile connectivity, with potential additional benefits of improved reliability of electricity provision, reductions in transmission losses and with increased opportunities for rural development. Several barriers to implementation for mini-grids in India highlights the need for supportive policies and a more enabling environment.

- Section 3 explores the options for mini-grid system design. Designing sustainable mini-grid systems to provide affordable, sustainable, reliable and modern access to electricity services to communities requires an understanding of the services they must deliver, the generation resources they have access to, and an assessment of how these will interact over the lifetime of the system. Using energy system modelling and techno-economic analysis can allow system designers to explore the options and opportunities for mini-grids to meet the present energy needs and those of the future as the communities develop.

- Section 4 evaluates the technologies which facilitate mini-grid deployment. Rapidly developing technologies can support the effective design of solar mini-grid systems. As established and emerging solar and storage technologies gain further deployment worldwide, the resulting cost decreases of these technologies could reduce the equipment costs of mini-grids and potentially provided more affordable electricity to rural communities. Opportunities for solar and storage mini-grids to interface with other generation sources or the national grid could further improve the overall reliability of electricity access, especially in India.

- Section 5 investigates the electricity demands of rural communities. Understanding the needs and priorities of a community, and therefore the electricity services that can satisfy them, is critical in designing effective mini-grid systems that can support those needs. Particularly for mini-grids which provide first access to electricity, estimating demand and how it might grow over time as the community develops is challenging, but methods of estimation have received much recent attention and continue to develop. Quantifying and categorising community demand profiles for domestic, productive, agricultural and community uses is very important. Variations and patterns of electricity demand can significantly affect the design of an affordable, sustainable and effective mini-grid, able to serve multiple end uses and to support increasing levels of demand as communities develop over time..

- Section 6 discusses real-life deployment challenges in India, the potential of mini-grids to support communities' development, and ownership and implementation models. The suitability and viability of mini-grids to provide electricity access to unelectrified and partially electrified communities in India is discussed, taking into consideration the different attributes of electricity provision: affordability, reliability, and ability to deliver modern electricity services to support communities' wider socio-economic development.



2. ELECTRIFICATION AND MINI-GRID IMPLEMENTATION IN INDIA

India has implemented a series of policies which have rapidly increased the number of electricity connections throughout the country. Electrification rates are high, but the quality of service from the grid, and the proportion of households that have access within an "electrified" community, varies within and between states.

- Mini-grids are a cost-effective, low carbon option to provide reliable electricity access in India and support the challenge of the last mile electrification.
- Around 1,800 mini-grids have been deployed by 2019 in India and it is forecasted that they will provide reliable power supply to 290 million people by 2027 (Sustainable Energy for All and Bloomberg NEF, 2020b).
- Many challenges to large-scale implementation of mini-grids need to be addressed by the state and central governments, including the regulatory and enabling environments, payment management, and the subsidised rates of grid power.

2.1. INDIA'S CLIMATE CHANGE AND ELECTRIFICATION COMMITMENTS

Under its nationally determined contributions to the Paris Climate Agreement, India is expected to reduce its emissions intensity of electricity by 35%, with renewable sources projected to comprise 50% of national energy generation by 2030 (Climate Action Tracker, 2021). Since the late 2000s several policies have been developed to mitigate GHG emissions from electricity production and, more recently, to support the development of solar mini-grids (CEEW Working Group on Mitigation Instruments, 2019).

The Perform, Achieve, Trade (PAT) Scheme, administered by the Bureau of Energy Efficiency, was established in 2008 under the National Mission for Enhanced Energy Efficiency to reduce the energy consumption of energy-intensive enterprises including thermal power plants (IEA, 2021b). Renewable Energy Certificates were introduced to incentivise large consumers of fossil fuel-based electricity to generate or purchase renewable energy, but experienced limited success (UKICERI, 2020).

The Jawaharlal Nehru National Solar Mission (JNNSM) was launched in 2010, to promote solar power usage with an original target of 20 gigawatts (GW) of installed capacity by 2022. A further goal of the scheme was to promote the availability of technical expertise and support facilities for renewable energy projects in India, and so many technical training programmes were implemented throughout educational institutions in India (IEA, 2020a). The Mission resulted in awareness amongst the teachers and students of technical institutions, along with newer products, publications, and start-ups.

The next government, under the leadership of Narendra Modi, adopted its National Electricity Plan (NEP) in 2018 with the ambitious targets in terms of reductions of CO_2 emissions from electricity generation, through an increase in renewable energy installations but also with an increase in capacity of coal fired power plants as shown in Figure 2.1. Estimates suggest that India could achieve even more ambitious CO_2 emission reduction targets if it would reduce new-build coal-fired power plants and investments in renewable energy would increase (Climate Action Tracker, 2021).

Meanwhile, the original target of 20 GW of PV installations under JNNSM was surpassed in 2018, four years ahead of the 2022 deadline, and the current ambitious target for 2022 was revised to 100 GW. The NEP had also revised the overall renewable energy target to 175 GW to be achieved by 2022, along with the additional schemes for e-mobility and energy efficiency to reduce the emissions at all levels.

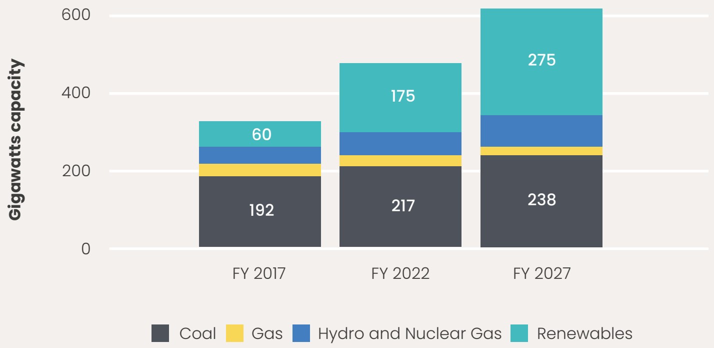


Figure 2.1. Breakdown of electricity generation capacity in India's National Electricity Plan 2018 (Institute for Energy Economics & Financial Analysis, 2018).

Considering the weak national grid, which results in losses of service, and the heavy curtailment rate of renewable energy generation (CEEW, 2018), local renewable energy generation, including mini-grids, will be critical to reach the unelectrified population with low transmission losses and expenditure on infrastructure.

In particular to provide last mile connectivity renewable based mini-grids (with capacities of 10s to 100s of kWs) can provide cheaper alternative solutions to grid extension while mitigating greenhouse gas emissions from fossil fuel-based power plants (see also Section 1.3) (Mandelli et al., 2016; Sustainable Energy for All, 2019a). To promote mini-grids in India, the Government issued a draft national policy in 2016 on renewable energy-based mini-grids. The policy proposed to set up at least 10,000 renewable energy-based micro- and mini-grid projects across the country, with 500 MW of generation capacity to be developed by private players by 2022 to cater around 237 million people who experiences energy shortage (Business Wire, 2020), but the policy has not yet been finalised (Centre for Science and Environment, 2020).

The status of electrification in India

Until recently, India was home to the largest number of people without access to electricity in the world. To address this, in 2005 the Rajiv Gandhi Grameen Vidyutikaran Yojana Mission began with the goal of providing electricity access to the entire population of India, and free electricity to households living below the poverty line (Banerjee *et al.*, 2015). In August 2013, this programme was brought under the new Deendayal Upadhyaya Gram Jyoti Yojana Scheme and began with great momentum to electrify rural India.

Under the current government initiatives, India has been reported as a success story in improving access to electricity: the electricity access rate has quickly improved from 66% in 2010 to 87% in 2018 (WEO, 2018). Also, the Rural Development Ministry estimated that around 14,700 villages were without electricity access in 2018. Meanwhile, the new Saubhagya Scheme was launched in 2017 with the goal of providing the last mile connectivity and electricity connections to all the unelectrified households in rural areas and economically poor unelectrified households in urban areas. It also aimed to provide solar standalone systems for unelectrified households located in remote and inaccessible villages, where grid extension is not feasible or cost-effective. Around 40 million unelectrified households in the country were targeted for electricity connections by December 2018 under this scheme and, in March 2019, the Indian government announced having reached full electricity access (IEA, 2021c) as 99.99% of the villages in India were electrified, as per the Saubhagya Scheme dashboard.

This led to criticism from different corners and media platforms, as some villages in India were still yet to access electricity services. The reality is shown by the definition put forward by the Ministry of Power, in which they claimed that a village is defined to be "fully electrified" if 10% of the households had electricity connection, along with the public places such as schools, panchayat [village council] office, health centres and community centres (Basumatary, 2021). Whilst a village may be considered electrified, the situation on the ground in which many people may have no access to electricity can be a very different reality.

In addition, the national-scale picture fails to capture the variation in levels of electricity services experienced throughout the country. Being a subcontinent of huge population, India is politically divided into 36 entities: 30 states and 6 union territories (Rajya Sabha Secretariat, 2021). The huge differences between these states in terms of languages, culture, economic development, and the local state government policies created differences in their overall development and electrification progress. As per the World Bank data, 97.8% of Indian households were electrified by 2019 (The World Bank, 2021). The India Residential Energy Consumption Survey, conducted in 2020 by the Council of Energy, Environment, and Water (CEEW) (Agrawal *et al.*, 2020), found broadly similar results overall, but disparities between urban and rural areas. A summary of their results, found by surveying nearly 15,000 households in 1,210 villages, and 614 wards in 152 districts across 21 states, is shown in Figure 2.1. Even though 2.4% of the Indian population remains unelectrified, another 0.33% are relying on the off-grid electricity sources (Agrawal *et al.*, 2020). In the survey, majority of the households reported that their inability to afford grid connection is the reason for not having a connection.

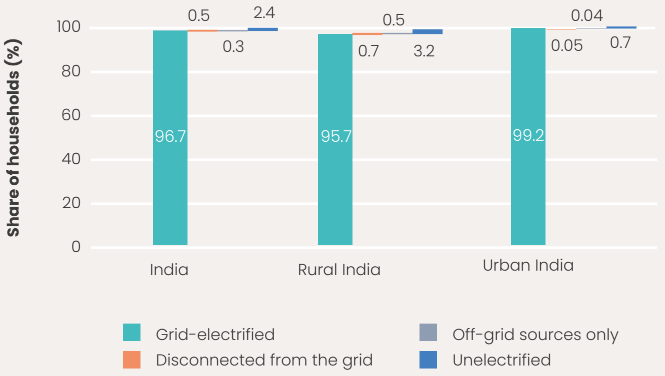


Figure 2.2. **Electrified and unelectrified share of households in Rural and Urban India, from** Agrawal *et al.*, (2020).

About 3.5% fewer rural households in India were electrified via the grid than urban households. The urbanisation rate is not uniform throughout the country (Esri, 2021); among the larger states, Tamil Nadu is the most urbanised with 48.4% of people living in urban areas, whilst Bihar has only 11.3% (Ministry of Housing and Urban Affairs, 2022). A key finding from the CEEW survey was that the majority of the unelectrified population are from the few states in north central India. Most of these people live in rural areas of the states of Uttar Pradesh, Madhya Pradesh, Rajasthan, and Bihar. Improving electricity access in these states will be critical in meeting the Saubhagya Scheme's goal of 100% electricity access.

2.2. FROM COUNTING CONNECTIONS TO HIGH-QUALITY ELECTRICITY

Many Indian homes and villages have access to the grid, but the supply of electricity is unreliable or unpredictable. As per the survey report of CEEW, electricity supplied through the main grid is often not available throughout the day: the 96.7% of households electrified via the grid receive an average of 20.6 hours of electricity per day, and this differs between urban (22 hours) and rural (20 hours) areas. In the north-central states of India, which have low electrification rates, the electricity availability is only 18.5 hours per day (Agrawal *et al.*, 2020). Among the electrified population, two-thirds of rural and two-fifths of urban households still face outages at least once a day. The daily power supply availability in different states of India is given in Figure 2.3.

A recent survey was conducted by the Smart Power India Initiative of the Rockefeller Foundation among the 10,000 rural consumers and businesses in four different states (Sustainable Energy for All and Bloomberg NEF, 2020b). It revealed that even though most respondents were located within just 50 metres of an electricity pole, in Uttar Pradesh around 32% of small businesses rely on only solar, mini-grids, lead-acid batteries, or diesel generators rather than using the electricity from the grid. Similarly, around 36% used other sources instead of the grid in Bihar. An additional 18% and 32% of people in Uttar Pradesh and Bihar respectively were found to use those off-grid technologies in conjunction with the grid to bridge the 9-12 hours of power failure in each day.

Figure 2.4 shows the availability of the grid and the usage of the grid only, both the grid and non-grid sources, and non-grid sources only for rural businesses in the states of Uttar Pradesh, Bihar, Odisha, and Rajasthan. It reveals that the non-grid energy usage is very high in these states due to the poor reliability of the grid, and that distributed energy options are not only viewed as an option for areas unreached by power lines but instead can be seen as a complement to the grid to provide additional services to the consumers.

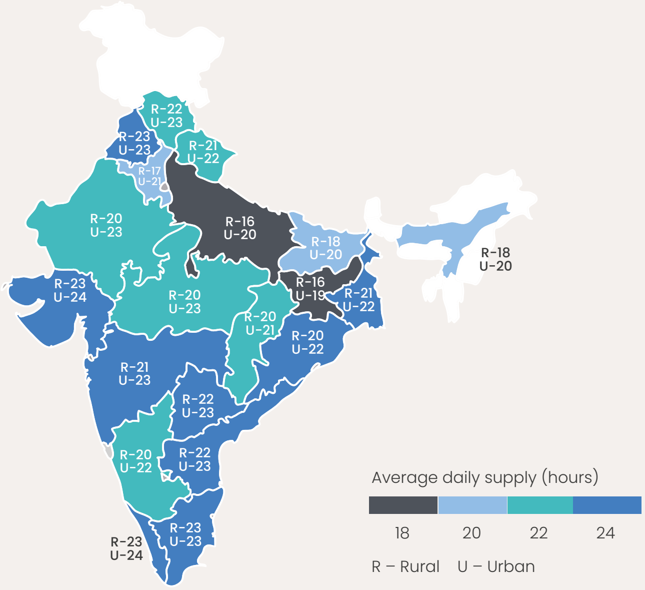


Figure 2.3. Average daily power supply availability in different states of India (Agrawal *et al.*, 2020)

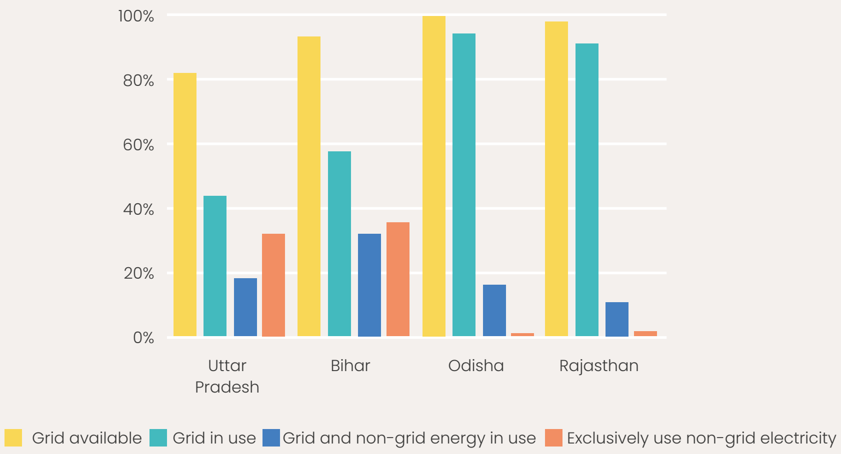


Figure 2.4. Available and used electricity options among small rural enterprises in India (Sustainable Energy for All and Bloomberg NEF, 2020b).

2.3. MINI-GRID DEPLOYMENT IN INDIA

Progress to date

Considering the challenges of last mile electrification in India, mini-grids are a cost-effective low carbon option to provide reliable electricity access, in particular to more remote and rural areas (Palit and Sarangi, 2014). Indeed, India has deployed 1,792 mini-grids by 2019 (Sustainable Energy for All and Bloomberg NEF, 2020b). A report by GMI Research on the India mini-grid market, published in 2020 and forecasting for 2020-2027, suggested that the rising emphasis on providing the reliable power supply to 290 million people will accelerate the demand for mini-grids in India (GMI Research, 2020).

Solar mini-grids have been implemented in India since the late 1980s and have been supported by schemes and programmes such as the Village Energy Security Program and Remote Village Electrification Programme, along with other energy-related state government schemes.

From 1996 to 2011-12 the West Bengal Renewable Energy Development Agency, Odisha Renewable Energy Development Agency, and Chhattisgarh Renewable Energy Development Agency, in partnership with private local agencies and private organisations, have installed mini-grids to supply energy for the local community (Jaffer, 2016). The state of Uttar Pradesh adopted a mini-grid policy in 2016 to speed up the electrification process (IEA, 2021d). Similarly, the Tamil Nadu state government's Solar Energy Action Plan 2023 (SEAP23), with a target of 9000 MW of solar system capacity, announced a series of training programmes for bankers to create awareness on solar energy project financing and through that making credit lines easily accessible. Many smart mini-grids for campuses and villages were initiated through the Tamil Nadu Energy Development Agency (Scherfler, 2020).

In 2017 most of the mini-grids deployment were concentrated in the northern and eastern part of the country, with the majority of the plants based on solar PV and a large concentration of hydroplants in the northeast (see Table 2.1 and Figure 2.5). A majority of these mini-grids had been set up by defence agencies in the upper reaches of the Himalayas, not easily reached by the national grid (Subramony, Doolla and Chandorkar, 2017).

Despite this support many systems are dysfunctional, survive due to new external funding, display very limited functional performance and, in many cases, have been abandoned. The reasons for these dysfunctionalities include inefficient planning of budgets, business models, human resources and insufficient understanding of community and stakeholder needs and capacities. The successful mini-grids are largely attributed to unique individuals, private funded stakeholders, or creative collection and maintenance techniques, which are rare to find.

Currently there is increased funding, investment, and promotion of mini-grids as they are viewed to provide a ready solution for meeting rural India's energy needs. A peaking interest in the private sector and impact investing has brought back the attention on solar powered mini grids: the Rockefeller Foundation, for example, and its Smart Power India programme in collaboration with Tata Power is implementing 10,000 mini-grids throughout rural India to serve nearly 5 million homes by 2026 (Singh, 2019; Sustainable Energy for All and Bloomberg NEF, 2020b). In addition, OMC Power plans to own and operate 500 mini-grids in Uttar Pradesh; the MLinda Foundation is implementing 100 mini-grids in Jharkhand; and Boond plans to experiment with 50 mini-grids for very poor communities. Many other investors are working across Indian states such as Maharashtra, Odisha, Bihar, Jharkhand, Uttar Pradesh, and West Bengal, considering the current opportunities and energy access issues. Meanwhile newer private corporations, institutions, and local NGOs are trying to become a rural energy services companies, officially recognized by the Indian Government (Jaffer, 2016).

PROJECT/DEVELOPER	MINIHYDRO	SOLAR PV	BIOMASS	WIND
Sidrapong hydel power station	✓			
Sagar island migrogrid		✓	✓	✓
Dhamal solar city		✓		
Chhattisgarh Renewable Energy Development Agency (CREDA)		✓		
Decentralized Energy Systems of India (DESI) Power			✓	
Husk Power Systems (HPS) micrograds			✓	
Orissa Renewable Energy Development Agency (OREDA)		✓		
West Bengal Renewable Energy Development Agency (WBREDA)		✓	✓	✓
Uttar Pradesh New and Renewable Energy Development Agency (UPNEDA)		✓		
Mera Gao Power (MGP)		✓		
Sikkim Renewable Energy Development Agency (SREDA)	✓	✓		
Gram Oorja, Naturetech Infra, and Minda Nexgen tech projects		✓		
Alamprabhu Pathar: Maharashtra Energy Development Agency (MEDA)			✓	✓
Solar electricity company (SELCO) foundation microgrids		✓		
Amrita self-reliant villages	✓	✓		
Gosaba island project			✓	
Biomass energy for rural India projects			✓	

Table 2.1. A summary of selected mini-grid projects in India by generation source, from Subramony, Doolla and Chandorkar (2017).

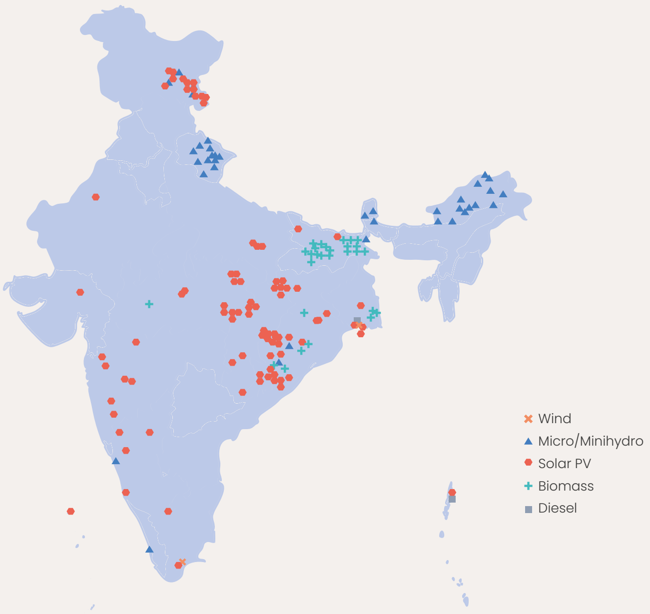


Figure 2.5. **The locations of selected mini-grid projects in India, from** Subramony, Doolla and Chandorkar (2017).

Barriers to implementation

High investment costs and low access to capital

A barrier that stands in the way of distributed renewables, including mini-grids, in achieving their potential in India is the high taxes on critical renewable energy components, which has been further increased by the central government from 5% to 12% since October 2021 in the form of Goods and Services Tax (GST). This resulted in a hike of overall project cost of 12% to 15% and could make the future renewable energy projects more expensive (Business Standard, 2021). This increase in capital investment creates a challenging environment to attract investment in renewable energy markets because returns have long been modest, and they are associated with high risks.

These challenges are particularly relevant for smaller-scale distributed energy players, such as mini-grid developers, which tend to be small and undercapitalised, lacking the balance sheets to start new projects. In addition, returns from mini-grids can take longer to realise compared to other energy sector projects. Therefore, mini-grid developers tend to struggle in accessing capital and in leveraging a project financing approach to access long-term debt, unlike larger developers of infrastructure assets. Without scale and cost reductions, however, long-term financing remains elusive (The Rockfeller Foundation, 2020). Policies must therefore be streamlined to make sure that financing is more accessible to mini-grid developers. For example, nationalised banks could be provisioned to provide long-term financing at lower interest rates (Jaffer, 2016).

Poor management and affordability issues

Although the Government has a clear goal for rural electrification, the success rate in India is still poor due to the financial inability of state government-owned distribution companies (DISCOMs) to invest in central grid expansion. The Indian constitution provides a division of power to states and central government: the 67 DISCOMs, mostly owned by the states, have faced chronic physical commercial and technical losses due to the lack of metering and low payment collection rates, leading to high levels of debt and delayed payment or non-payment to generators (IEA, 2020a). Among the grid connected households in India, 93% have metered connections but only 91% of those metered connections are billed regularly. In addition, 83% of the remaining consumers pay electricity bills in cash through collection agents or DISCOM counters, even though 70% of the Indian households have a smartphone (Agrawal *et al.*, 2020). Mobile money or electronic payments, which have supported the growth of mini-grids throughout Africa, is much less common in India.

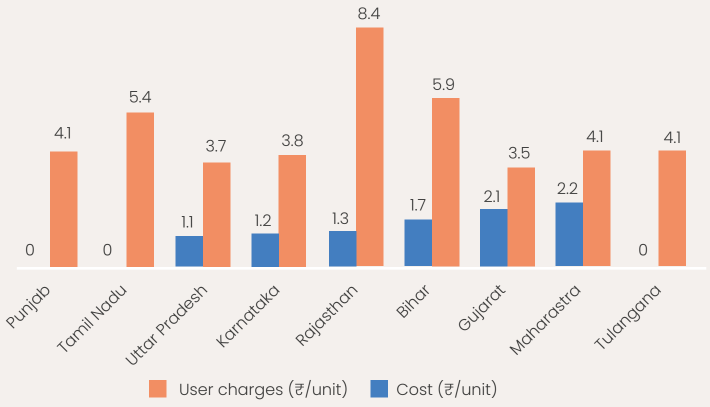
In a recent survey of rural households in the state of Assam, it was revealed that the households living below the poverty line were shocked to receive an electricity bill of more than INR 65,000. In other parts of the state, the average monthly electricity bill is INR 2,500 for a household below the poverty line which uses only two lamps during the night which may cost around INR 150. Initial research on the high electricity cost revealed that the problem was due to the provision of non-metered grid connections from 2016, and the collection of lower monthly charges (INR 100-200) until 2021 by the Assam Power Distribution Company Limited instead of actual usage-based charges. Now the same consumers are charged for the whole units consumed from the day the meter was connected, in addition to the surcharges as a penalty, which has led to default payments for months (Basumatary, 2021). These rural households have been overburdened with energy bill indebtedness, along with energy poverty, due to the poor management system.

The inability of a household to pay the monthly bill is not only a barrier to energy access, but also a critical element to support financial sustainability of mini-grid investments. Introducing stricter policies, like cutting off energy due to the non-payment of monthly bill, could create a strong culture of regular payments among the consumers (Jaffer, 2016).

Subsidised electricity tariffs

India's economy is mostly agrarian due to the huge dependency on farming and agriculture. Historically, providing free power to the agricultural sector helped parties to win state elections, as it was considered an important policy instrument to woo farmers (Fosli, Reddy and Rani, 2021). From 1980s, most of the Indian states provided free or heavily subsidised electricity for agriculture, under the pretext that the suicide rates reduced when free electricity was provided in drought-affected areas, that farmers cannot afford electricity at open market rates, and free power is essential to increase their profits (Shah, Giordano and Mukherji, 2012).

Free power to agriculture is commonplace in states like Andhra Pradesh, Tamil Nadu, Telangana, and Punjab. Free electricity for irrigation pump sets is a popular demand by farmers, as irrigation increases farm incomes by two to three times compared to non-irrigated areas. The actual cost of energy and the agricultural user charges in selected states is given in Figure 2.6. This has resulted in huge losses to the state-run DISCOMs as the overall energy consumption of Indian agricultural sector is 17.69%. As a result, this free or subsidised electricity rates hinders the rate of grid extension by inducing high costs for the DISCOMs and demotivates the use of mini-grid among rural households due to the latter's higher cost of energy, compared to the subsidised electricity from the grid. A particular challenge will be how to transition farmers from not paying electricity for irrigation to the market value for this service.



Source: Ministry of Power, Government of India (2019)

Figure 2.6. User charges and cost of electricity for agriculture in the different states in 2019 (Fosli, Reddy and Rani, 2021).

No regulatory framework for grid extension

Private investment in mini-grids is low in India, due to poor government policies and regulatory frameworks related to both the development of new mini-grids, and future extension of utility lines into the areas which are already covered by the mini-grid.

Under the current regulations, any prospective entrepreneur in India is permitted to build a mini-grid and subsequently provide electricity services in the area covered by said installation without any licence or certification. On the other hand, there is no legal or regulatory framework that specifies what is to happen if the central grid were to be extended to an area that is already covered by a mini-grid (Comello *et al.*, 2017).

The switching of consumers to the grid, particularly due to its subsidised costs, could therefore create a huge loss for the mini-grid investors. Additionally, experiences from other countries in South and South-East Asia have suggested that there is not yet a good solution to integrate mini-grids into the main grid, and hence most of the mini-grid facilities were abandoned (Tenenbaum, Greacen and Vaghela, 2018).

Government-owned utilities, which provide most of the electricity in India, could instead view distributed generation-based suppliers as a complementary effort to their plans to electrify the unserved and underserved populations (Jaffer, 2016).

They are perceived as competitors, however, even though mini-grids support the utilities by providing locally-generated power supply to remote communities. Mini-grids could reduce requirement for high grid expansion costs, bulk investments in new power plants and help in reducing transmission and distribution losses as well as GHG emissions (Comello *et al.*, 2017). In addition, mini-grids can support local electricity bill collection from its end users, as this is a main problem faced by most of the utilities in India (Gupta, 2021). Likewise, a robust regulatory legal framework for the extension of grid and utilisation of existing mini-grid infrastructure is necessary to attract entrepreneurs for making the investment in the face of that risk (Comello *et al.*, 2017).

BOX 2.1: ABB AND HUSK POWER SYSTEMS, TPRMG AND AIRTEL

The multinational companies like ABB and TATA power are collaboratively working with the local companies in India to fasten the rural electrification process through mini-grid and microgrid systems (Sustainable Energy for All and Bloomberg NEF, 2020a). ABB is working with the Husk Power Systems for installing, operating, and maintaining the mini-grid solutions. ABB provides the pre-wired and configured mini-grid solutions in different ranges so that the system can be setup within a day to provide supply to the rural customers by Husk Power System. It provides opportunity for the companies to focus on their own strengths. ABB provides high-quality equipment while Husk Power Systems uses their local market experience to meet the need of the local customers. The Husk Power Systems turned to solar and solar-Biomass hybrid systems from their own biomass-based mini-grids.

TP Renewable Microgrid (TPRMG), a venture by a TATA Power, completed the installations of 200 mini-grids and plans to rollout 10,000 mini-grids in future (Singh, 2019). TPRMG partnered with Airtel Payments Bank to enhance customer convenience by enabling the rural customers to pay their bills at neighbourhood payment locations operated by local entrepreneurs.

3. SYSTEM DESIGN

Designing effective solar mini-grid systems requires an understanding of technology performance and community demand for electricity services. Energy systems modelling, techno-economic assessment and life cycle analysis provide a framework for designing sustainable mini-grids.

- Computational simulation and optimisation models can evaluate a variety of potential system configurations
- Economic and environmental assessment criteria are used to compare candidate systems before implementation.
- Solar mini-grids can be designed to provide electricity access for a variety of community uses, and to support economic and community development.

3.1. INTRODUCTION

The system design process bridges the gap between conception and implementation of an energy system by moving from the initial identification of an energy need and towards the practical considerations of procurement and installation. It can also evaluate the expected long-term performance of a system and could help to highlight any potential issues during its operation.

Energy system modelling offers a way of investigating how a mini-grid system might perform: by computationally simulating the individual technology components, the electricity services demanded by the community, and the subsequent energy flows within a system it is possible to evaluate many potential system configurations and investigate how they might perform during implementation. Applying techno-economic analysis, which combines the technical performance of the system with the economic, environmental or other impact criteria, it is possible to identify candidate systems which could meet specific ends uses and demand and, ultimately, select the most promising system for implementation.

The practical implementation will be subject to a variety of further considerations – such as the details of how its technological components will interact in practice, the policy regulations they must adhere to, and the financial model they will operate under – but energy system modelling can provide a valuable first step in exploring the viability of a potential system to provide affordable, reliable and sustainable electricity.

3.2. DESIGNING MINI-GRIDS

Methods

Many energy systems modelling tools, and particularly those used for mini-grid design, use computational simulations to assess how an example combination of technologies meets a load profile, representing the electricity needs of a community. By then varying the types and capacities of the technologies, the system designer can compare the performance and impacts of many potential options for system designs. Energy system models can therefore help to explore which system configuration would be most suitable in providing electricity services to a community and have been used extensively to investigate rural electrification systems around the world, and particularly in India, shown in Figure 3.1.

Energy system models also allow designers to explore a range of potential future use scenarios. Changing the load profile, for example to increase electricity demand over time, could be used to evaluate the long-term performance of a system as a community develops economically. Simulating different electricity prioritisation strategies, for example preferentially using energy generated from solar power ahead of the national grid, could also be used to understand how to get the greatest value from the installed assets. Each of these simulations and scenarios could reveal trade-offs between different system design options and their impacts.

Figure 3.1. The number of optimisation-based studies focusing on rural electrification systems for each country (blue circles) and the national electrification rates (percentages) identified by Akbas *et al.* (2022).

The most commonly used energy system model for mini-grid design is HOMER (HOMER Energy LLC, 2022), a well-established commercial software which can model and optimise a wide range of technologies, energy use scenarios and analysis criteria (Sen and Bhattacharyya, 2014; Amutha and Rajini, 2016; Bahramara, Moghaddam and Haghifam, 2016). HOMER is the world leader in mini-grid system design and has been used in a large number of academic studies as well as in the design of real-life systems around the world. There are also a number of free, open-source energy system models available for system designers: CLOVER (Sandwell, 2022), developed at Imperial College London, is a techno-economic model for simulating and optimising community-scale electricity systems and is also fully customisable for users to edit and add functionality to accurately represent their specific system requirements or operation (Sandwell, Ekins-Daukes and Nelson, 2017; Sandwell, Wheeler and Nelson, 2017; Beath *et al.*, 2021). Web-based applications, such as the JRC Photovoltaic Geographical Information System (PVGIS) (European Commission, 2019), can offer intuitive interfaces for estimating the performance of user-specified system designs across a wide geographical area.

System design requirements

Resource availability and technical performance

Understanding the availability of energy resources is particularly important for mini-grid systems which are often unconnected to a national grid network and might rely solely on a single energy source. Furthermore, considering how this resource availability might vary during the day, season or year will be critical in designing a system which is resilient to the natural variations in both supply and demand. This is often modelled by considering the generation potential of a single unit of a technology – for example 1 kWp of solar, 1 kWh of battery storage or 1 kW of diesel generation – and scaling this output to the capacity of the system being considered.

Solar resource availability is dependent on the time of day, year and climate, as well as on the location where the panels are installed(Deshmukh *et al.*, 2019). In India the average available solar resource can be as low as 4 kWh/day or as high as 7 kWh/day, depending on location (Mahtta, Joshi and Jindal, 2014), with further day-to-day and seasonal variations. The output of a solar panel will depend on solar irradiance but also internal factors, such as its efficiency and the technology being used (see Section 4 on technology development), and on implementation factors such as the orientation of the panel when installed and any shading from nearby trees or buildings. Depending on the level of detail required a simple assumption of a daily average generation could be used during the system design. More rigorously, solar generation could be derived by calculating the irradiance incident on a panel based on historical solar measurements and its orientation, combined with the technical performance of the panel. Alternatively a number of solar resource calculators are available: Renewables.Ninja (Pfenninger and Staffell, 2022), for example, is a free web-based interface which allows a user to download solar irradiance and generation data for any location around the world at an hourly resolution and is based on estimations from satellite measurements (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016).

Battery storage is used to match energy supply to the demand of a community. For solar-powered mini-grids this is fundamental in providing electricity throughout the evening, night time, and during periods of reduced solar generation such as cloudy weather. Different battery technologies will have various performance parameters (see Section 4 on technology development) but, fundamentally, energy system models compare the levels of supply and demand at a given time to calculate how much energy is drawn from or input into the available storage. Similarly to generation sources, battery storage is typically modelled based on a "unit capacity" of 1 kWh of storage which can be easily scaled to investigate the performance of different amounts of overall storage capacity.

Of the key criteria used in modelling the performance of batteries, the depth of discharge is one of the most important (Schiffer *et al.*, 2007). Cycling batteries between an upper and lower limit of capacity (for example between 90% and 40%) can limit degradation and improve longevity but limits the overall capacity of the battery to a fraction of its total (in this case 50%). Increasing the depth of discharge could reduce the number of batteries that need to be installed but introduce a trade-off against battery lifetime, for example. Another key criterion is the C-rate, which governs the rate at which batteries can be charged and the power available to meet the loads: a lower C-rate could also decrease battery degradation but limits the power than can be drawn at a given time. This means that energy may be available in the battery to meet the load, but not enough can be provided at that time, ultimately resulting in a shortfall. As mini-grid modelling software usually considers an hourly resolution, further work could be necessary to identify periods when shorter, high-power loads are in use.

Dispatchable generation, for example diesel generators and biomass gasifiers, can be modelled as either reactive to meeting demand as a backup, predictable in the times of the day when they are used, or anticipatory to charge batteries if they are likely to soon be depleted (Sandwell, Chan, *et al.*, 2016; Chambon *et al.*, 2020). Typically, these generation sources operate at a minimum load factor of 30-50%: if in use then the generator must output at least that fraction of its overall capacity regardless of the load being demanded, which can be inefficient at meeting smaller loads with large backup systems. These dispatchable generation sources can provide electricity systems with a security of supply which is not dependent on the availability of weather-dependent renewable resources, making them a potentially valuable and cost-effective component of "hybrid" mini-grids which rely on more than one generation technology (Chambon *et al.*, 2020; Baranda Alonso, Sandwell and Nelson, 2021).

Electricity from the national grid can also be included: grid-connected systems would require significant technological consideration for the practicalities of their interconnection, but are comparably straightforward to mode (IRENA, 2016; ESMAP, 2019). Electricity from the grid can be treated as an inexhaustible but time-dependent resource, emulating the situation in many rural areas in which periods when grid power is available are unpredictable, by using probability-based functions for availability. Buying power from the grid, or feeding it back into the national network during periods of local overgeneration, can also be included and can be used to explore the opportunities for different grid prices and feed-in tariff structures.

The overall performance of each of these sources, and others, are considered within mini-grid modelling tools. They also include how they are interconnected, for example by taking into account the efficiencies of transmission and from converting between DC and AC power or vice versa. The degradation of technologies over time and through usage can also be included and can be important for multi-year investigations and when technologies are employed in harsh environments (Sowe *et al.*, 2020). Accounting for these factors, and by comparing the energy available from each source and the load being demanded during each time step (typically one hour) over the length of a simulation period (typically several years), the model can evaluate the energy balance in the system overall and, as a result, calculate the overall performance of the mini-grid.

Electricity demand

A mini-grid system must be able to meet the electricity demand of a community, when it is demanded, in order to provide a reliable and sustainable service to its users. This can be through direct supply from renewable generation, backup sources such as diesel generators, or from battery storage, but the satisfaction of demand – measured in terms of whether or not the electricity services are provided at the right times – is one of the most immediately noticeable performance metrics by the community served by a mini-grid. Characterising demand for electricity services is a complex topic and is covered in more detail in Section 5. For the purposes of system design the key component is the load profile, a statement of the electricity demand (in kW or, equivalently, kWh per hour time period) for all times during the considered system lifetime. Similarly to electricity supply, this can vary throughout the day and across seasons.

Designing mini-grid systems relies on the total demand of the community aggregated across all users. The load is considered at the system level and, once combined, different demand types are usually treated equally. It can be useful, however, to categorise demands into different user groups such as domestic, commercial or institutional demands for later analysis of how well a system meets each of their needs. In some mini-grid design models it is also possible to segregate between critical and non-critical loads, prioritising the former if the availability of energy is (or is projected to be) low.

System costs

As most system design models focus on the capacities of different types of generation and storage technologies, a core input is therefore their costs (Arranz-Piera, 2017). The costs of mini-grids are usually divided into two categories (Arranz-Piera, 2017): capital expenditure (CAPEX), which includes investments in the system such as for equipment and infrastructure, and operational expenditure (OPEX) which refers to ongoing recurring costs such as maintenance, labour and rent. CAPEX costs are usually inputted as the cost per unit (for example per kWp of solar or kWh of storage) which is readily scalable comparably to the system sizing process. These capacity-dependent costs can be taken as representative values (for example average prices from literature searches) or could be derived from the actual prices of the technologies, for example the selling prices for panels or batteries being offered by local equipment companies. Associated costs which also vary depending on the capacity of equipment installed, such as mounting and wiring for solar panels, also should be accounted for.

Beside CAPEX and OPEX of mini-grid equipment and components, system designers must also take into account other fixed costs of mini-grid systems (Arranz-Piera, 2017). These could include site-specific investments such as for scoping studies, environmental approval, land, or community engagement. They could also include variable costs dependent on the ultimate extent of the system and number of customers, for example for the distribution network, metering and household wiring. Other system costs could depend on several factors, such as inverter requirements or interconnections between the mini-grid and the national network.

Life cycle analysis

Manufacturing system components requires energy and materials that release greenhouse gas emissions and other pollutants into the environment. Environmental databases such as Ecoinvent (ecoinvent, 2022) provide a standardised reference inventory of the environmental impacts of components and materials in terms of GHG emissions, use of scarce resources, land and water use, and other factors. Life cycle analysis (LCA) is a process through which these environmental impacts can be assigned to each component and, using these, a system designer can quantify the total for an entire system (Kittner, Gheewala and Kammen, 2016; Ludin *et al.*, 2018). In addition to the environmental impacts of components, system designers may also need to include logistical considerations such as shipping and transportation to a remote installation site. As presented later, the most common form of LCA focuses on the climate change impacts of electricity systems in terms of their greenhouse gas emissions (Ortega-Arriaga *et al.*, 2021). A schematic of LCA considerations is shown in Figure 3.2.

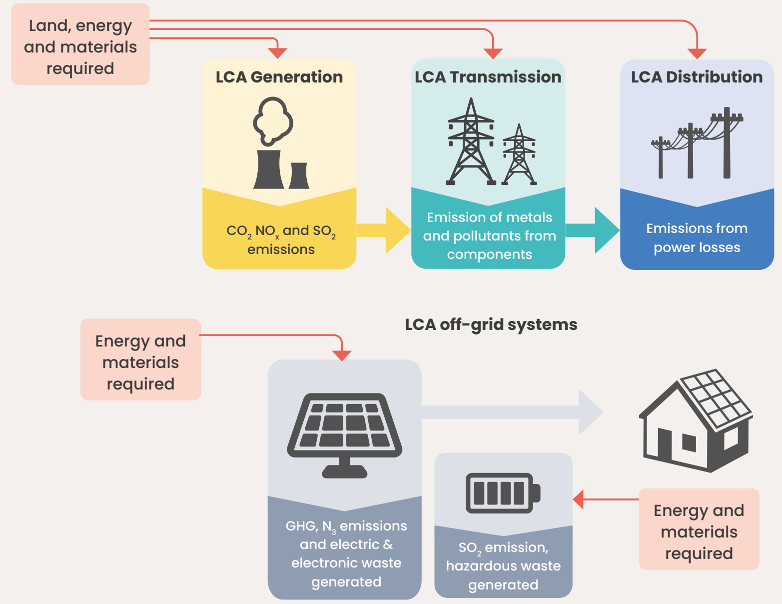


Figure 3.2. **A schematic of the inputs and considerations of LCA for grid generation, transmission and distribution, and for off-grid electrification options, from** Ortega-Arriaga et al. (2021).

3.3. ASSESSING SYSTEM PERFORMANCE

Once a simulation of a mini-grid has been undertaken a system designer can conduct an assessment of its performance to assess its suitability in meeting the needs of the community. In this context, meeting the need of a community results from the ability of the mini-grids to provide affordable, reliable, sustainable and modern electricity access (see also Section 1). This includes:

- Assessing and optimising system technical performance, i.e. the ability of the system to supply energy to reliably meet demand.
- Evaluating and minimizing economic and environmental impacts, i.e. the costs and greenhouse gas emissions associated with the system installation and operation, in order to achieve an electricity provision as affordable and sustainable as possible.

System performance can be assessed for different configurations of technologies or different capacities, to meet the needs of a community which can meet different type of constraints or priorities. For example, a system designer might insist that a system provides a given level of technical performance, such as a minimum number of hours of service per day. Of the systems that can facilitate this, they might select the system configuration that provides the lowest cost of electricity as the optimum. Further constraints could also be introduced, for example not exceeding a given initial investment cost, or environmental performance metrics might also enter into decision making.By simulating and assessing different systems configurations, a designer can select the one which best meets the needs and priorities of a community, developer and other stakeholder groups.

Technical performance

Computational modelling of mini-grid systems allows a designer to understand the flows of energy in a system, both in balancing the supply and demand but also in terms of the energy provided from each source. As the supply and demand may vary depending on the time of day and season, it also allows designers to quantify the reliability of the system in meeting demand and identify any potential shortfalls: either because the system capacities are too small, leading to systemic drops in electricity availability, or during periods when high demand is coincident with low supply.

An alternative way of measuring reliability is in terms of the proportion of energy demand being met or not, regardless of the times when demand occurs (Beath *et al.*, 2021). This can be beneficial if the load varies significantly throughout the day and meeting demand during certain periods is more important than others. For example, in a system with high productive uses of electricity (such as welding) or medical loads (such as X-rays) in the daytime, and with low demand overnight when these services are not used, a one-hour loss of power availability would be more impactful during the day, and this would be reflected in the proportion of demand being met but not in the overall hours of service availability (Beath *et al.*, 2021).

Neither of these reliability metrics take into account common real-life technical issues, for example equipment failures, which are typically not included in energy system models of mini-grid. Regardless of the projected reliability estimated by a model, systems operating in remote and rural areas will likely suffer shortfalls in electricity service caused by technical issues such as equipment breakages and faults (Hazelton, Bruce and MacGill, 2014). Furthermore, the resolution of the models – commonly hourly – cannot identify the effects of spikes in demand, varying solar generation owing to cloudy weather, or other power issues that could cause outages. Designing a system using these methods should therefore be supported by higher-resolution power systems analysis and demand estimation, presented in Section 5, to quantify and potentially mitigate these issues.

Other performance metrics could be related to the specifics of the technologies chosen, for example quantifying the fuel requirements of a biomass gasifier to ensure that sufficient feedstock is available throughout the system lifetime. The degradation of technologies can also be incorporated into the modelling processes and outputs, for example to predict decreasing capacities of batteries over time to estimate when they might require replacement.

Economic assessment

The levelised cost of electricity (LCOE) is one of the most common metrics for assessing the economic performance of a mini-grid over its lifetime (IRENA, 2016). This is typically reported in $/kWh (or a local currency) and generally offers a fair comparison between different types of systems, generation sources and applications. All the costs associated with the system installation and operation (CAPEX and OPEX) are summed annually and then "discounted", a process which uses a set rate to account for the decreasing value of money over time similar to interest charged on a loan. The sum for each year of the system lifetime is combined to give the total cost, and is then divided by the total energy provided by the system – similarly discounted – to give cost per unit of electricity ($/kWh). The LCOE provides the minimum tariff that should be charged in order for a system to break even, which can vary significantly between different types of technologies and use cases. The levelised cost of used electricity (LCUE, $/kWh) is a stricter definition of the LCOE which explicitly considers only electricity used by the community (Sandwell, Chan, *et al.*, 2016). This definition can be useful for solar mini-grids as, for example, its calculation does not include energy which is dumped owing to overgeneration from solar exceeding the demand the community, and can account for periods when electricity demand goes unmet.

Renewable mini-grids generally require higher up-front CAPEX investments compared to fossil fuel (such as diesel) systems, but have lower OPEX owing to their reduced maintenance requirements and often negligible fuel costs. These are important factors when considering the capacity of a mini-grid development: a system with a low lifetime LCOE might have high CAPEX requirements which could be beyond the investment available. Furthermore, initial CAPEX investments are relatively penalised by the discounting process used in the LCOE calculation and so considering the entire lifetime of the system, and the overall financing structure. It is important therefore to reduce mini-grids CAPEX as much as possible to ensure economic viability Lower CAPEX would then imply lower LCOEs and tariff charged, hence making the mini-grids more affordable to final end users.

Historically, mini-grids have had higher LCOEs compared to utility-scale generation owing to their smaller scale and the necessary investments in local infrastructure, such as battery storage or distribution networks (see Figure 3.3) (Sandwell, Chan, *et al.*, 2016). At present global mini-grid LCOEs are around \$0.55/kWh, but falling technology costs and innovations (as discussed in Section 4) could drive this to below \$0.22/kWh by 2030 – projecting mini-grids to be the lower-cost option compared to grid extension worldwide (ESMAP, 2019). Mini-grids are already more cost-effective in terms of generation cost compared to grid extension in locations where the distance to the existing grid network would make the requirements to build new transmission infrastructure too costly (Nouni, Mullick and Kandpal, 2008; Sandwell, Chan, *et al.*, 2016; Ortega-Arriaga *et al.*, 2021). However, when the cost for the final users in taken into account, electricity provided by mini-grids tend to be more expensive in presence of subsidised grid electricity (as for example in India).

Nonetheless, as discussed below, solar mini-grids can offer improved opportunities for reliable electricity services, and lower-carbon electricity, compared to the national grid network for a range of domestic, productive and community applications (Beath *et al.*, 2021).

Environmental impacts

System modelling can help in identifying the mini-grid configurations with the lowest climate change or local environment impacts. The total embedded emissions of a system, typically measured in tCO$_{2eq}$, measures the overall climate change impact of the system in a manner comparable to the total lifetime economic cost. It can be calculated analogously by considering the emissions embedded in equipment production, for example, similarly to CAPEX and those from operations or fuel usage, similarly to OPEX. This metric can compare the total emissions of renewable systems (mainly embedded emissions from system equipment) against fossil-fuel or hybrid systems (mainly emissions from fuel use during operation), and can also be used to investigate which renewable-powered mini-grid has the lowest impact, for example solar mini-grids compared to those powered by other renewable sources.

The emissions intensity, or specific emissions, of a mini-grid is given by the total embedded emissions (in equipment and operation) divided by the amount of energy provided over its lifetime. This is comparable to the LCOE (albeit not using discounted values) and is typically measured in gCO$_2$/kWh. Like the LCOE, this metric is useful in comparing mini-grids systems serving different needs (such as the community size or demand being met) as well as comparing them to the emissions intensity of the national grid network. The emissions intensity for off-grid mini-grids is typically higher than for utility-scale renewable projects owing to the former's embedded emissions of the battery storage and distribution network (Sandwell, Chan, *et al.*, 2016).

Comparing different system configurations (for example one powered by diesel to a renewable alternative) can also be done by considering the marginal abatement cost (MAC) (Baranda Alonso, Sandwell and Nelson, 2021). The MAC is calculated by dividing the difference in total cost between an incumbent and an alternative system by the difference in total emissions between the two. This yields a metric typically measured in \$/tCO$_2$, which can represent the economic cost of offsetting one tonne of CO$_2$. Replacing cheap, high-emissions systems with more expensive renewable alternatives results in a positive MAC and, by implementing projects with the lowest MACs first, this can mitigate emissions in a cost-effective manner. As the costs of renewable technologies have decreased it is increasingly common to have a negative MAC: by switching to the renewable alternative a mini-grid developer can both reduce costs and lower CO_2 emissions.

In addition to the greenhouse gas emissions, other environmental impact metrics can be included in the system design and assessment. Comparing the use of different storage technologies, for example, could reveal differing usage of scarce materials or resources. It could also be useful to assess the impact on the local environment from the leakage of pollutants from the system, either during operation or through improper disposal. The costs and environmental impacts of component decommissioning, and the opportunities for local recycling, can also be included in the wider system economic and environmental assessments.

3.4. MINI-GRID DESIGN IMPLICATIONS FOR DIFFERENT DEMAND TYPES

Solar mini-grids designed to provide services aligned with Tiers 2 or 3 in the Multi-Tier Framework (Bhatia and Angelou, 2015) (such as several hours of availability during the day and evening for lighting, phone charging and entertainment services such as televisions or radios) can be supplied by relatively low-cost systems (ESMAP, 2019). The main design considerations would likely be to ensure good reliability during the evening, when most users would require services, and a low LCOE to make the system affordable for the community. Other useful metrics could be the potential for the system to offset current sources of lighting, such as kerosene lamps.

Solar mini-grids are also well-suited to providing power for productive and income-generating activities (Ganguly *et al.*, 2020; Hartvigsson *et al.*, 2021), such as for machinery, agro-processing equipment, refrigeration or tailoring, which are typically concentrated during the daytime when the solar resource is highest. Providing power into the evening, additionally, could promote longer or more flexible working hours and extend the opening times of shops or businesses beyond sunset. As productive energy demands are typically higher than domestic ones, a system designer might design a system which focuses on meeting these productive loads.

In some systems it is more critical to provide the highest Tiers of electricity access, with high-capacity power available throughout the day and night, for example in health clinics. A health clinic may already have access to power, for example through a diesel generator, and so solar power could be introduced to reduce fuel costs and emissions (Baranda Alonso, Sandwell and Nelson, 2021). A designer could consider combinations of solar and battery capacities, backed up by the diesel generator to ensure a 24-hour service, which could offset the greatest amount of fuel (Babatunde *et al.*, 2018). A comparison to the diesel-only system could also be used to calculate the marginal abatement cost (MAC) to evaluate the relative financial costs of mitigating GHG emissions. In a healthcare setting it may be particularly important to analyse the power balances in the system to ensure high-power equipment, such as X-ray machines, can be used without causing disruption (see Section 5).

Typically, as system sizes are increased, and the loads being met are diversified LCOE could decrease as the number of connections increases, potentially increasing the affordability to the community, but the overall system cost will also increase (Sandwell, Ekins-Daukes and Nelson, 2017). As communities develop economically their electricity demand might also increase and, with it, a need for increased generation capacity to satisfy those needs (Richmond and Urpelainen, 2019). The modular nature of renewable technologies makes them well-suited to this challenge: integrating additional solar or storage capacity to an existing mini-grid is relatively straightforward and can be used to meet this growing demand (Sandwell, Ekins-Daukes and Nelson, 2017; Riva *et al.*, 2019; Stevanato *et al.*, 2020). In a community with growing demand, diversified loads can reduce the relative need for storage compared to solar capacity, but overall could increase the LCUE and emissions intensity of electricity as higher-level services become more widely available, shown in Figure 3.3 (Few *et al.*, 2022). The implications of different types of community demands, and the impacts on system sizing, are presented in Section 5.

As this section has described, designing effective mini-grid systems relies fundamentally on the ability to model the performance of electricity technologies and an understanding of their financial and environmental impacts. There are many available options for solar and battery storage technologies and, as these develop, so do their technical performance, costs and embedded GHG emissions, whilst new technologies emerge. The following section presents the present status and recent developments of these technologies to discuss their potential effects on solar mini-grids.

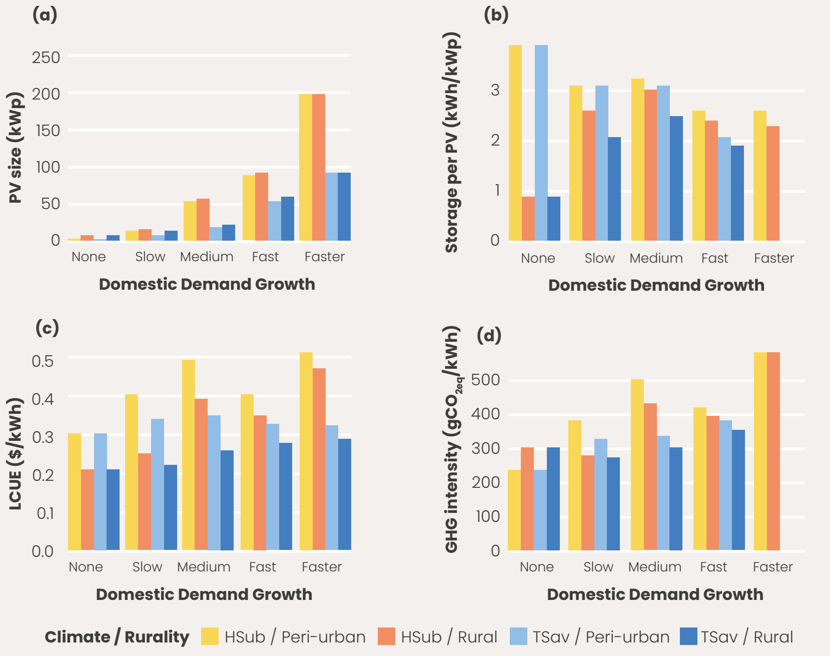
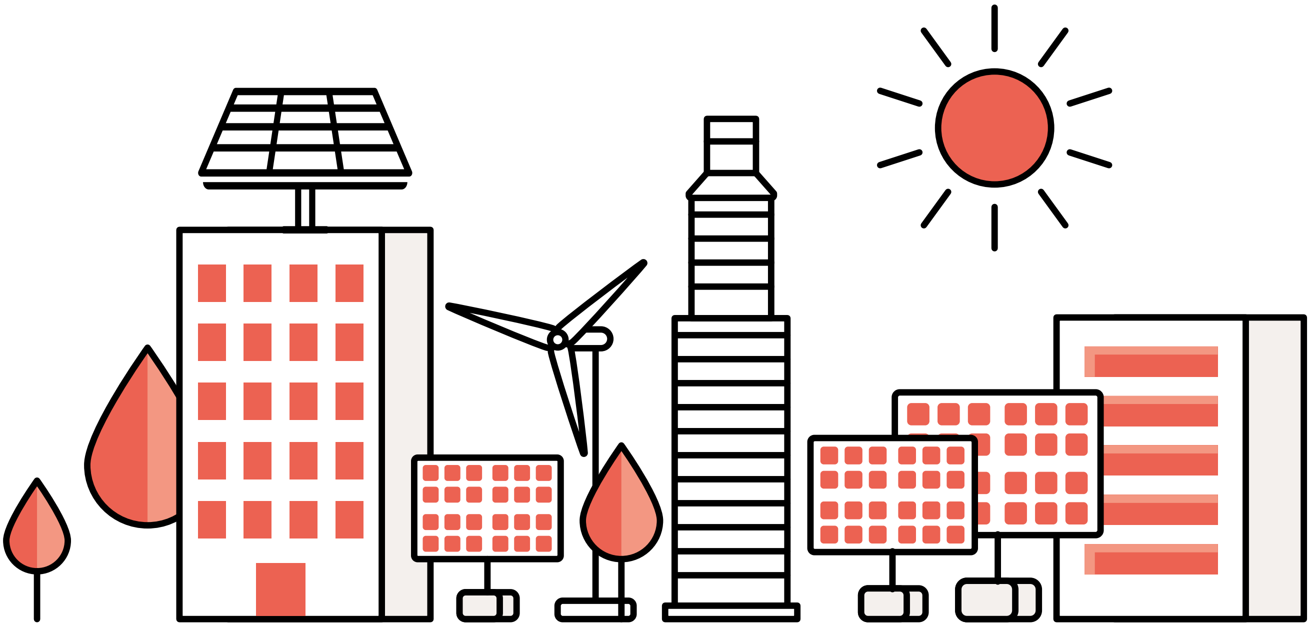


Figure 3.3. The effects of different speeds of growth in community demand on PV size, relative storage requirements, (c) cost of electricity, and (d) emissions intensity on two example ruralities (peri-urban and rural) and two climatic conditions (humid subtropical and tropical savanna) (Few *et al.*, 2022).



4. TECHNOLOGY DEVELOPMENT

Technological developments and falling prices have made solar mini-grids more affordable. Future innovations in battery technologies, in particular, could further reduce costs and improve performance for off-grid electrification in rural areas.

- Solar mini-grids have benefited from low PV panel prices, driven by the global increase in PV deployment.
- Price decreases for energy storage will continue to further drive down the cost of electricity in mini-grid systems, with lithium-ion batteries expected to be the prominent technology.
- Maintaining the long-term performance of batteries in rural environments will be critical in ensuring reliable and sustainable electricity services.

4.1. INTRODUCTION

The rapid pace of technology development has implications for the design and cost effectiveness of mini-grid systems, as well as on their ability to serve the combined objectives of improved access to electricity and GHG emissions mitigation. A recent interview study identified commercial readiness, capital cost, technology performance, financial stability of the provider, and technological development as key considerations in technology choice amongst mini-grid providers (Few, Schmidt and Gambhir, 2019). As such, both technical improvements and the enabling environment is required for technologies to realise their full potential in a mini-grid.

Solar PV technologies, in particular crystalline silicon (c-Si) technologies, have experienced remarkable and largely unexpected (Candelise, Winskel and Gross, 2013) decreases in production costs since 2009-2010, due to rapid expansion of production capacity (see Figure 4.1).

Between 2009 and 2020, PV modules prices have declined between 89% and 95%. Global PV installations have also been growing over time. By the end of 2020, over 707 GW of solar PV systems have been installed worldwide, representing a 16-fold growth since 2010, and global PV installed capacity is projected to reach around 10 TW by 2050 (Polverini, Dodd and Espinosa, 2021) . As a result, the global capacity weighted-average total installed cost of projects commissioned in 2020 was 81% lower than in 2010 and 13% lower than in 2019 (IRENA, 2021).

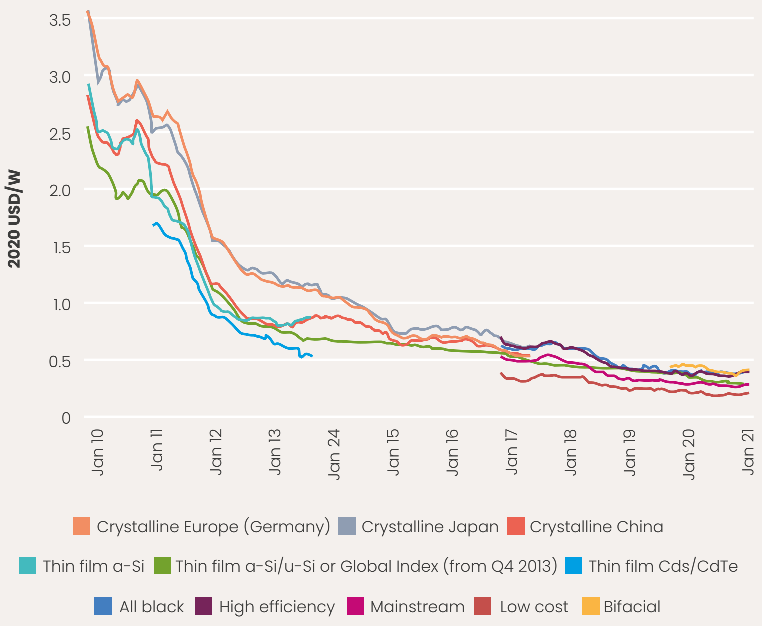


Figure 4.1. Average monthly solar PV module prices by technology, 2010-2020 (IRENA, 2021).

These cost reductions have made PV the most predominant technology used for mini-grids over the last decade (see Figure 4.2). In 2019, 55% of operating mini-grids used PV as the generation technology. This trend is expected to continue, in particular in remote rural areas as they are relatively easy to install and are the most cost-competitive technology, unless low-cost resources such as biomass and small-hydro are available (SE for All and Bloomberg NEF, 2020).

Lithium-ion battery costs continue to fall, predominantly driven by scaling up of production for the electric vehicle industry (Nykvist and Nilsson, 2015; Few, Schmidt, Offer, *et al.*, 2018). Battery lifetimes are also increasing, driven by better understanding of degradation pathways and fundamental/engineering improvements (Few, Schmidt and Gambhir, 2019).

These continuing technological improvements help to position solar mini-grids as a more affordable and reliable source of sustainable power in rural areas (ESMAP, 2019). This chapter will mainly focus on this specific technological configuration for mini-grids, by discussing how technological developments (including new technologies, improved supply chains and projected cost reductions of system components) could improve technical and economic performance of mini-grids, and the wider technological landscape both globally and in India.

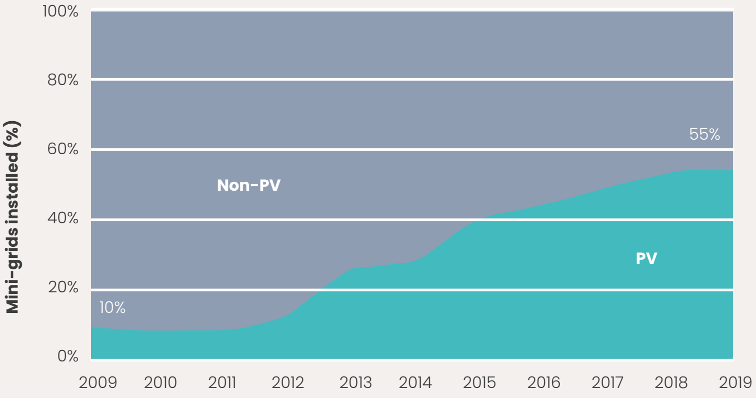


Figure 4.2. The proportion of mini-grids using PV and non-PV generation sources (Sustainable Energy for All and Bloomberg NEF, 2020b).

4.2. MINI-GRID TECHNICAL STRUCTURE

A mini-grid is a local electricity system which incorporates generation, distribution, and storage within a controlled network. It is a form of decentralised electrification that may or may not be connected to the grid, and as such includes the necessary components to operate as an interconnected system or entirely independently. When interconnected, the "island mode" is a self-sustaining independent energy system when power from the grid is unavailable. Electricity generation can be from one or several energy resources (renewable or not) and the electricity supplied can be alternating or direct current (AC or DC). Mini-grids can provide power to communities or institutions of any size, including rural villages, hospitals, university campuses or even towns (ARUP, 2021). An example layout of a mini-grid is shown in Figure 4.3.

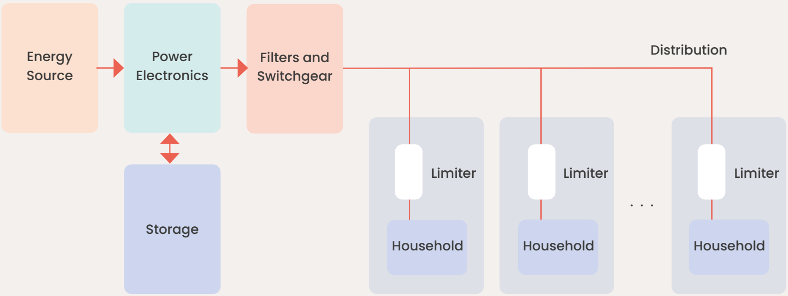


Figure 4.3. An example structure of a mini-grid layout (Subramony, Doolla and Chandorkar, 2017).

Table 4.1 highlights advantages and disadvantages of using AC and DC power in mini-grid networks. For smaller mini-grids, DC reduces inverter losses and system costs but has a more limited range of appliances which run on DC directly.

For larger mini-grids, AC can transmit power more efficiently over larger distances and the range of appliances that are commercially available is much larger. Furthermore, an AC mini-grid distribution network could be used to transmit power when a reliable grid connection for the system becomes available.

There remains several technical challenges relating to mini-grid control which must be addressed to ensure power quality. There may be a need to coordinate generation, loads, and storage in real time, however control systems and power electronic converters can be used to maintain voltage and frequency, as well as other methods such as demand side management.

	ADVANTAGES	DISADVANTAGES
Alternating current (AC)	• Well-developed product standards • Plug and play • Low voltage (LV) AC electrical systems is a global market	• Increased conversion requirements (DC to AC to DC) • Energy losses in conversion • More equipment and greater costs
Direct current (DC)	• DC produced by PV and stored by batteries • DC used in consumer electronics • Lower conversion requirements • No need for inverters so reduced losses on conversion	• Lack of LV DC distribution system and standards • Limited market and familiarity with LV DC • Safety protocols different to AC • Fewer high-power appliances

Table 4.1. The advantages and disadvantages of AC and DC distribution in standalone mini-grids.

4.3. SOLAR PHOTOVOLTAICS

Current status and development trajectory

Power generation from PV technology is one of the most accessible forms of renewable energy and worldwide growth in installations has helped support its more nascent application to solar mini-grids.

The first generation of PV technologies, based on crystalline silicon (c-Si) wafers, are one of the oldest and most mature technology and includes single/monocrystalline (m-Si) and multi/polycrystalline (p-Si). C-Si covers over 90% of PV market share, with m-Si (33%) and p-Si (53%) making up the majority (Wilson *et al.*, 2020). Solar cell efficiency for m-Si and p-Si PV cells reached 26.7% and 22.3% respectively, however commercial wafer-based silicon PV modules achieve only up to 17% (Wilson *et al.*, 2020).

In terms of durability, c-Si PV can provide 20-30 years of good performance under outdoor exposure and its energy payback period (at which the energy generated by the panel is greater than that used to manufacturer it) lies between 1-4 years, depending on the geographical location of installation. However, one of the biggest challenges with PV technology is the variability of solar radiation and its performance degradation at high temperatures. Furthermore, the efficiency of c-Si PV has a strong linear and negative correlation with temperature, reducing its efficiency in hotter climates and intense sunlight. Cold water or air flow on the top or back of the PV system can improve its efficiency, however the deposition of dust and insufficient rain to self-clean the panels can reduce the power generation and deteriorate overall efficiency (Ghosh, 2020b). Furthermore, regular cleaning via manual or robotic methods, or application of anti-soiling coatings on the PV surface, can minimise these issues.

Solar PV offers far lower GHG emissions than the national grid network of India: life cycle analysis (LCA) indicates that PV emits only 35 gCO$_{2eq}$/kWh over its lifetime, compared to 1,138.8 gCO$_{2eq}$/kWh from coal power plants (Ghosh, 2020a). Whilst c-Si dominates the PV market share, cadmium telluride (CdTe), a thin-film PV technology, requires much less energy in its production and hence can have lower GHG emissions associated with its manufacture (Fthenakis *et al.*, 2020). In addition to its production, a challenge for PV is to reuse or recycle the waste generated from the solar panels: as PV panels cannot be reused directly after their lifetime, recycling is a major issue and proper end-of-life disposal incurs both financial and GHG burdens. LCA found that recycling accounted for 13-25% and 3-4% of the lifecycle impacts of c-Si and CdTe technologies respectively (Maani *et al.*, 2020).

A typical c-Si PV system consists of an aluminium alloy frame, a tempered glass cover, ethylene-vinyl-acetate to encapsulate the cells, a silicon panel, a back sheet, silver bus bars, tin wires, and adhesive sealants. Aluminium and glass account for 90% of the total volume of the panels, thereby indicating high potential of usable resources across various types of PV technologies. Increased efficiencies, thinner wafers and wires, and the usage of larger ingots led to significant reduction in the usage of materials for silicon cells: from 16 g/Wp to around 4 g/Wp over the last 13 years, which also benefitted from a decrease in price of silicon from 475 $/kg to 25 $/kg (Fu, James and Woodhouse, 2015). Solar PV panel waste is estimated to be 78 million tons globally, which could equate to $15 million if materials are recovered efficiently. For India, the estimated waste generation is around 8 million tons, with an estimated value of $1.5 million (Pankadan, Nikam and Anwer, 2021).

Emerging technologies

Emerging PV technologies could offer new cost reductions, environmental benefits, or other advantages over existing solar panels and their usage in solar mini-grid systems. Types of emerging PV include organic photovoltaics (OPV), Perovskites, and dye-sensitised solar cells (DSSC) with flexible, lightweight, and convenient designs with multicolour options and transparency variations. These technologies have widespread advantages over silicon and thin film PV, such as weak temperature dependency on efficiency (Bhandari *et al.*, 2020) which improves their relative performance in hotter climates. These technologies absorb lower amounts of infrared light than silicon technologies, and therefore have lower thermal coefficients. They also have disadvantages, however, including faster degradation in performance owing to encapsulation issues and therefore shorter lifetimes than established PV technologies.

Simpler and lower-cost manufacturing methods and less time-consuming fabrication are other potential advantages of these new technologies. The current efficiencies of OPV, Perovskite and DSSC are approximately 18%, 25.5% and 12% respectively (Green *et al.*, 2021), however issues with these technologies include their instability under moisture, humidity, temperature, and UV light. Each of these issues limit their large-scale production and deployment, however these could be mitigated as the technologies mature. Saule Technologies, OPVIUS, Dyesol, Exeger Sweden AB, Fujikura Ltd are a few of the commercial producers of these emerging technologies.

During the manufacturing process, emerging solar PV technology consume less energy, with a positive environmental impact as compared to c-Si or thin film solar PV. For example, OSC PV system shows 39-89% lower LCA impact than silicon (Tsang, Sonnemann and Bassani, 2016). Perovskite-based PV systems have severe environmental issues as most of the highest efficiency cells are made by lead, however further research will enable us to replace them with environmentally benign technology.

Energy payback for these types of emerging solar technologies are less investigated than their mature counterparts, but vary from 1-4 years depending on the type of material employed and their cell efficiency (Ghosh, 2020a). These new technologies are commercially available but not yet widely, although possess considerable potential for future integration into a range of solar application – including distributed power in solar mini-grids.

4.4. BATTERY STORAGE

Current status and development trajectory

Energy storage technologies are an essential component of mini-grids to provide power when intermittent renewable energy sources are unable. Of the various technologies, electrochemical methods have recently received significant industrial uptake, in part due to their modularity, flexibility and rapid response. Key drivers for this include capital cost ($/kWh), lifetime cost of storage (LCOS, c/kWh/cycle) and round trip efficiency (%), with Table 4.2 comparing the key metrics between different candidate technologies.

These costs of storage technologies are highly dynamic, especially for those less well-established. With regards to the capital cost, the intrinsic materials used are obviously important, however Schmidt *et al* (2017) suggest that – regardless of the technology – stationary energy storage systems are on a capital cost trajectory to 340±60 $/kWh once 1 TWh of installed capacity is achieved. This is, in part, due to economies of scale and improved learning rates, shown in Figure 4.4. This figure also highlights the significant difference in price when factoring in system integration, which can account for approximately 50% of the total cost. Here ancillary components include battery management systems, thermal management systems and enclosures.

Of these technologies, lead acid batteries are one of the most well established and mostly used to date in mini-grids applications (see Figure 4.5). They are commonplace in automotive low voltage systems, powering ancillary functions such as engine start-up, and to date has >1 TWh deployed. However, in grid applications there has been less uptake, in part due to the challenges with lifetime and efficiency, as well as improvements in other technologies such as lithium-ion batteries. This is highlighted by works such as Dhundhara, Verma and Williams (2018) which performed a techno-economic analysis comparing lithium-ion batteries and lead acid batteries in mini-grid applications, and found lithium-ion to be the superior technology. However, the technological maturity of lead acid batteries, increased safety characteristics and ease of implementation, do offer near term advantages over lithium-ion batteries which has seen their application in smaller scale energy storage systems.

TECHNOLOGY	PUMPED HYDRO	COMPRESSED AIR	LEAD ACID BATTERY	LITHIUM-ION BATTERY	ELECTROLYSER/ FUEL CELL	REDOX FLOW BATTERY
Capital cost ($/kWh)	10-100s	10-100s	10-100s	100s	1000s	100s
Lifetime cost of Storage (c/kWh/cycle)	<1-10	<1-10	10s-100s	10s-100s	100s-1000s	10s
Round trip efficiency (%)	70-85	50-75	65-85	80-90	<40	65-85

Table 4.2. Comparison of different energy storage technologies for the grid. Adapted from Few *et al.* (2016).

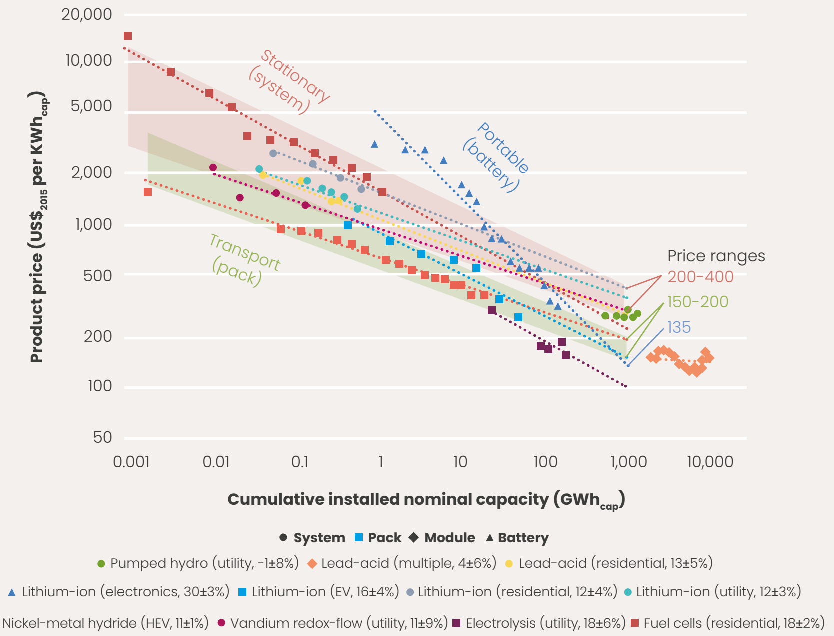


Figure 4.4. Future costs of energy storage technologies at 1 TWh from Schmidt *et al.* (2017).

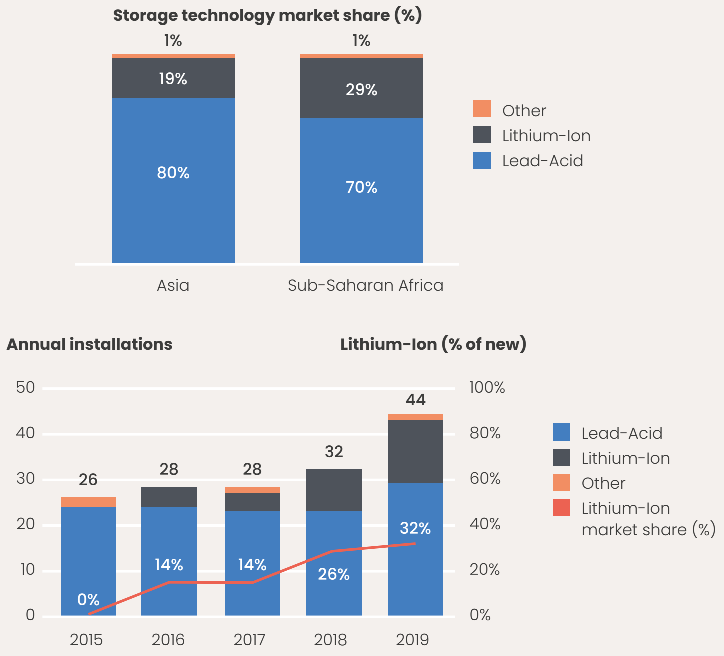


Figure 4.5. The share of battery technologies installed in mini-grid by region, and over time (Sustainable Energy for All and Bloomberg NEF, 2020a).

Cost improvements are still needed, however, and increasing adoption of lithium-ion batteries for road transport electrification is likely to benefit stationary mini-grid applications through economies of scale. Expert elicitation studies by Few, Schmidt, Offer, *et al.* (2018) further suggest that near term improvements will likely arise from engineering improvements of the system, with slight improvements in the battery chemistry. However, more transformative technology changes are possible by 2030, assuming aggressive R&D funding. Further work from Schmidt *et al.* (2018) suggested that, on a lifetime cost of storage (LCOS) basis, costs are likely to fall between a third to a half between 2030 and 2050, with lithium-ion battery technology likely to become cost competitive by 2030.

Within the family of lithium-ion batteries, there also exists a number of different battery chemistries which are qualitatively compared in Table 4.3 (adapted from the work by Hesse *et al.* (2017)). Batteries consisting of nickel manganese cobalt oxide (NMC)/Graphite (Gr) and nickel manganese aluminium oxide (NCA)/Gr have experienced the most aggressive cost reductions due to uptake in the automotive industry. Lithium-iron phosphate (LFP)/Gr cells are rapidly becoming one of the most cost-effective lithium-ion battery technologies and are safer than NMC and NCA chemistries (in term of thermal runaway characteristics), making them attractive for stationary applications such as solar mini-grids.

In the context of India, and irrespective of chemistry, operating conditions remain a significant challenge, where lithium-ion battery lifetime is highly sensitive to temperature. In these conditions, thermal management systems to regulate the temperature of the batteries will almost certainly be required, which increases the system cost but also the overall energy efficiency. Furthermore, battery degradation is highly non-linear and a function of factors such as current, state-of-charge and temperature, with near-term improvements likely to be found with management via more intelligent model-based control of these devices and battery digital twins (Wu *et al.*, 2020). The value of model-driven approaches was highlighted by Reniers *et al.* (2020) who showed that control algorithms, informed by a physics-based model, could increase the revenue from a grid-connected battery by 20% whilst at the same time decreasing degradation by 30% compared to simpler linear models of battery performance.

In the near term, lithium-ion battery technology is likely to be the prominent technology. The economies of scale that are being achieved in the automotive sector will bring benefits to stationary mini-grid applications, with chemistries such as NMC, NCA and LFP the most likely to be deployed. However further improvements are needed, with system integration costs identified as a key challenge, although improvements to system engineering and intelligent control of these devices is likely to yield near-term improvements.

For the Indian storage market these improvements are welcome, however supply chains for these systems are largely non-indigenous. This could represent an additional barrier to deployment in the country. This was highlighted by Olivetti *et al.* (2017) who showed that, apart from graphite, India does not have meaningful resources of battery-relevant metals such as nickel, manganese, cobalt and lithium, with these dominated by China, the Democratic Republic of Congo, Chile and Australia, amongst others. Sun *et al.* (2019) also confirmed this, but also noted the geographical stratification both when considering the refining/manufacturing of the raw battery materials into precursors, and also the manufacturing of this into the batteries (mostly dominated by China, Japan and Korea).

Emerging technologies

Beyond lead acid and lithium-ion batteries there are a range of technologies being considered for large-scale energy storage applications. This is motivated by the need for increasing device lifetime and lower cost, both of which would have beneficial effects on the overall viability and affordability of solar mini-grids. In that respect, promising technologies which are currently being considered for mini-grids include redox flow, sodium-ion, and aqueous batteries.

PARAMETERS	NMC/GR	NCA/Gr	LFP/Gr	LFP/LTO
Cost per kWh	+	+	++	–
Safety	–	–	+	+
Maturity	Market	Market	Market	Niche
Cycle life	–	–	+	++
Calendar life	+	+	++	+++
Energy density	+	+	–	––
Power density	+	+	++	+++

*NMC = Nickel Manganese Cobalt Oxide | NCA = Nickel Manganese Aluminium Oxide | LFP = Lithium Iron Phosphate | LTO = Lithium Titanate Oxide | Gr = Graphite

Table 4.3. Qualitative comparison of different lithium-ion battery technologies for grid applications. Modified from Hesse *et al.* (2017).

Redox flow batteries are particularly promising for longer duration energy storage systems due to their ability to decouple power and energy, and their potentially high lifetimes. Various studies have suggested that for more than four hours of storage, common in rural mini-grid systems, flow batteries become advantageous compared to lithium-ion batteries, with potential costs being half that of lithium-ion on a $/kWh basis (Skyllas-Kazacos *et al.*, 2011). These devices work by having two electrolyte tanks which effectively store the energy, which is then passed through a flow battery stack where the electrolyte is effectively charged or discharged.

A diversity of different electrolyte combinations currently exist, with reviews such as Skyllas-Kazacos *et al.* (2011) providing an excellent overview. To date, two main flow battery technologies have seen moderate industrial uptake: all-vanadium flow batteries and zinc-bromine systems. These have both been deployed in demonstrator projects with scales ranging from the kWh to MWh scale (Kear, Shah and Walsh, 2012), however capital cost remains a major barrier, with this in the region of 800-400 $/kWh for the all vanadium system (Zhang *et al.*, 2012). Cost benefits are realised at larger scales, indicating a potential misalignment with mini-grid applications in rural areas. The zinc-bromine system has further challenges in that, if not properly managed, toxic bromine can be produced; the reversibility of zinc is also not perfect, resulting in the need for periodic reconditioning cycles.

Beyond these chemistries, there is currently significant interest in the area of organic flow batteries, where the costly inorganic electrolyte (e.g. vanadium) can be replaced with cheap and earth abundant organic molecules. However, the stability of the molecules and the relatively low performance has hindered their industrial deployment to date (Leung *et al.*, 2017).

There is also broad interest in the use of sodium-ion batteries in stationary applications. This technology works in a similar way to lithium-ion batteries, however it replaces the more costly lithium with more earth abundant sodium. However, whilst this is advantageous, the absolute amount of lithium in a battery is relatively low and the swapping of the charge carrier does not result directly in large cost reductions (Vaalma *et al.*, 2018). However, indirect benefits such as the ability to replace the copper current collectors with aluminium and the ability to store cells at zero volts provides broader benefits which merit their investigation in mini-grid systems. This does, however, come with the drawback of reduced specific energy, generally poorer lifetime than lithium-ion, and currently higher cost due to the absence of economies of scale. Yet, despite these challenges, companies such as Faradion in the UK have demonstrated technical industrial feasibility of the technology, though this is still a relatively embryonic energy storage technology from a deployment perspective.

This constant drive towards cost reduction for stationary grid applications has also reignited interest in aqueous (water containing) batteries due to the environmentally benign nature and potentially low cost of these systems. A comprehensive review of these technologies is presented by Posada *et al.* (2017) with key metrics outlined below in Table 4.4. Of note within this family of technologies was the commonly referred to “salt-water” battery, which companies such as Aquion had previously attempted to commercialise. The operating mechanism of this battery is detailed by Whitacre *et al.* (2012) and consists of a low-cost manganese dioxide cathode and carbon anode, within an aqueous sodium-ion based electrolyte. The combination of low-cost electrodes and electrolytes was the main attraction of this technology and various demonstrator units were deployed, however lack of industrial uptake ultimately limited broader deployment.

Thus, within the broader context of grid scale energy storage and the functions it can provide, there is not currently a technology which completely fulfils the requirement of every function at all scales. Therefore it is envisaged that there will likely be a portfolio of technologies available to meet the diverse set of energy needs (Gür, 2018), and so the most suitable storage technology for each solar mini-grid may vary between application, location and budget.

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
Lead acid	Abundant raw materials, low cost	Low energy density, limited cycle life, toxicity
Sodium-ion (MnO_2/C)	High energy density, high round trip efficiency, relatively long cycle life	Yet to demonstrate scalability
Zinc-air	High energy density, low cost, environmentally friendly, abundant raw materials, easy to scale	Short cycle life, low efficiency, self-discharge
Iron-air	Low cost, environmentally friendly, abundant raw materials, easy to scale	Low coulombic efficiency, low energy density, self discharge

Table 4.4. Comparison of selected aqueous batteries. Adapted from Posada *et al.* (2017)

4.5. OTHER GENERATION TECHNOLOGIES

Whilst we have focussed on solar generation and batteries for mini-grid architectures, there are several other possible generation technologies. Solar energy is widely available over most of India, but this is not the same for other renewable energy sources, with the suitability of each is dependent on the available local resources.

Bioenergy is commonly used in India: it is the predominant energy source for cooking, although there are schemes to try to promote cleaner cooking with bottled gas and biogas such as the Pradhan Mantri Ujjwala Yojana (Ministry of Petroleum and Natural Gas, 2021). However, there are also applications for use in mini-grids. Gasification is a controlled process that limits oxidation and temperature to allow for energy carrier gases to be produced from biomass. Research and development have led to installations for the gasification of solid biomass to produce syngas that can be burnt in an engine to produce electricity (Blanchard, 2015). In India several small-scale gasification plants have been built for example, a 35 kW gasifier has been installed in Bihar State, making use of waste agricultural rice grain husk, linked to a compression ignition engine to provide electricity for businesses and up to 500 households (Ashden, 2011).

Hydropower (or Hydel) has existed in India since the earliest days of electrification: the Sidrapong Hydel Power station in Darjeeling was a 130 kW mini-grid commissioned in 1897 (Suryad, Doolla and Chandorkar, 2017). Hydropower mini-grids are geographically distributed particularly in the northern hilly areas of India such as Sikkim (see also Section 2.3). The southern State of Kerala also has numerous micro hydro projects, for example the 20 kW Vortex Micro hydroelectric Project at Kaduvetti Bridge [5]. Micro-hydro power grid projects have been installed at Thayannankudy, a tribal colony inside the Chinnar Wildlife Sanctuary, and Eachampetty, near Marayu, Kerala (Thiruvananthapuram, 2018). With regards to wind power, India lacks sufficient resources over much of the country (Technical University of Denmark, 2022). Areas with the greatest resource are typically in the west of the country.

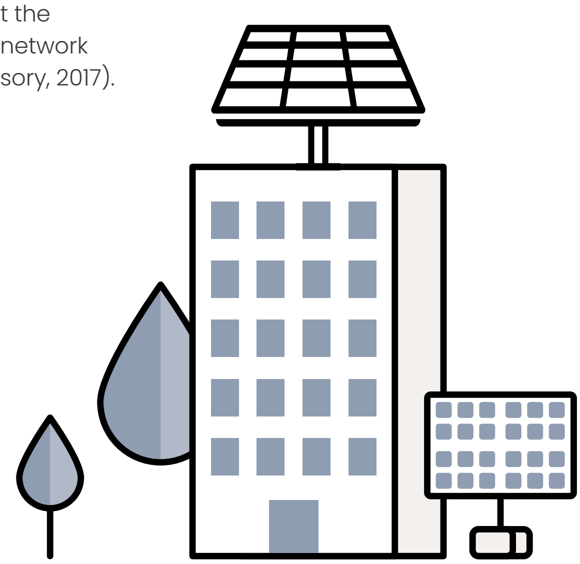
Whilst individual renewable energy technology mini-grids have been proven to work in India, it is also beneficial to utilise more than one resource where possible in the form of hybrid mini-grids comprised of several parallel connected renewable resources with electronic control strategies. As with other mini-grid architectures, these should be capable of operating in islanded and grid-connected modes where relevant. As discussed in Section 3 there are several system design advantages for using multiple generation technologies in hybrid mini-grids, including cost effectiveness, with their greatest advantage being that they avoid reliance on one potentially intermittent or seasonal source, thereby increasing the overall reliability of power supply

(Jayachandran and Ravi, 2017). - In the Sagar Islands in the Sundarbans, solar-wind-biogas mini-grids have been installed involving the community with responsibility for O&M and tariff collection (Suryad, Doolla and Chandorkar, 2017). A wind-PV-battery hybrid system will require fewer PV modules, a smaller wind turbine and fewer batteries than would be required for a PV-battery or wind-battery mini-grid. This makes the hybrid mini-grid more financially sustainable with lower capital and operational expenses (Jayachandran and Ravi, 2017).

4.6. INTERCONNECTION WITH THE NATIONAL GRID

The grid network in India has significantly expanded in terms of geographical reach and the number of communities connected (Indian Ministry of Power, 2021). The presence, or future expansion, of the national grid can undermine the perceived viability of mini-grid systems (see also Section 2.3) (Bhattacharyya et al., 2019; Graber *et al.*, 2019), but if a mini-grid and the national grid exist in the same location there is the possibility for both to work in tandem via interconnection (ESMAP, 2019). Grid-interconnected mini-grids, either resultant from the grid extending to a community with an existing mini-grid or as renewables capacity installed to augment grid power, could combine the benefits of resilient local generation with a cheaper but unreliable national network. In the case of rural India, the relative unreliability of the national grid network (Agrawal *et al.*, 2020) could be augmented by a connection to a solar mini-grid with the latter providing power when the former is unavailable. There are many technical challenges that must be overcome, however. The mini-grid must be able to independently operate in “intentional island mode” when the national grid is down, which might not be possible if the mini-grid relies on the main grid for frequency control (Tenenbaum, Greacen and Vaghela, 2018). Furthermore, when not properly isolated, islanded mini-grids might continue to supply power back to the main grid along transmission lines – these live wires could pose an electrocution risk to maintenance staff (Tenenbaum, Greacen and Vaghela, 2018). Finally, in India there is little explicit definition in the regulatory environment (such as governing the permission for a mini-grid to buy, sell and distribute power to the grid, and under what conditions) and the technical requirements (for equipment, power management and control) (Okapi Research and Advisory, 2017). These uncertainties make communities in grid-connected areas riskier to mini-grid developers, inhibiting their deployment and the potential of solar mini-grids to support the reliability of the main grid network (Okapi Research and Advisory, 2017).

Selecting the most appropriate technologies to supply a solar mini-grid is ultimately motivated by the ability of the system to meet the electricity demand of a community. Estimating this demand for electricity is therefore as critical as estimating the potential supply, with both varying in magnitude throughout the day and year. The following section describes the importance of estimating community electricity demand, the categories into which demand can be categorised, techniques for quantifying it, and the impacts on mini-grid systems as demand for electricity services grows over time.



5. DEMAND CHARACTERISATION

Understanding the needs of a community is critical in quantifying the demand for electricity and, therefore, the type and size of mini-grid system that can meet those needs. Estimating the energy requirements of a newly electrified community, and the subsequent impacts on the system design, can be challenging but several methods exist to categorise and control electrical loads.

- Demand can be categorised into domestic, productive, agricultural and community demands and the composition within a community affects the peak power requirements, daily electricity use, variability and predictability of demand.
- Estimation and modelling techniques can evaluate present demand and, importantly, estimate how electricity requirements might increase as the community develops over time.
- Load forecasting and demand management can help to ensure long-term system reliability, especially at higher levels of electricity access.

5.1. OVERVIEW

In order to provide access to affordable, reliable, sustainable and modern electricity a mini-grid must be able to serve the needs of a community and the electricity demand that meets those needs. The design of mini-grids must therefore:

- Provide a reliable electricity supply to serve the different community end uses, by ensuring its long-term technical performance and matching the community demand with local generation,
- Allow for affordable tariffs to be charged to end users, by optimising the system to reduce system costs and the cost of electricity,
- Account for a growth demand over time, allowing a community to increase through the Tiers of electricity access as it develops,
- Do this sustainably, by minimising the total GHG emissions embedded and used in the system.

Section 1 presented how, as a community (and its households, businesses and community facilities) develops, it can move through the MTF Tiers from access to basic electricity services to high-power uses and appliances. Section 3 introduced how mini-grid system design and optimisation are strongly dependent on the load profiles of the end users that it serves, and the categorisation of those electricity users into households, businesses, agriculture processing, community facility, and other types of demand. A detailed characterisation of community demand is therefore crucial to design successful and sustainable mini-grid systems.

Increasing electricity usage as the community develop is not universal, however, and can require diverse complementary activities to realise the social and economic benefits that electricity access can bring (Riva *et al.*, 2018). Demand characterisation for both initial access to electricity and growth in demand over time is a complex matter, still requiring considerable research and monitoring. There is nonetheless considerable ongoing work on demand characterisation for appropriate system sizing (Cader, Blechinger and Bertheau, 2016) and this section discusses the major demand characterisation challenges, solutions and modelling tools.

5.2. DEMAND CHARACTERISATION FOR OPTIMAL MINI-GRID SYSTEM DESIGN

For last mile connectivity and communities newly gaining access to electricity, it can be challenging to estimate the services and electricity demands that will be required. In this case, several demand estimation and characterisation techniques, described in this section, can be employed which consider different factors about the community and their needs. The Multi-Tier Framework, described in Section 1, can also serve as a guide especially for initial electricity access: providing basic lighting, phone charging and entertainment services (Tiers 1 and 2) might have relatively predictable electricity needs, whilst higher-power appliances (Tier 3+) and the growth in productive uses, as communities develop, might require further analysis. As the needs and electricity usage of the community grow, so does the overall electricity demand, and hence the need to design systems which can accommodate both the electricity needs at present and in the future – founded upon a quantification and characterisation of these needs.

Defining magnitude of the demand

Every electricity appliance (such as lights, phone chargers, machinery, medical devices) consumes electricity when in use. The demand is the amount of power (in watts) that an appliance consumes when it is in use. Naturally, the usage of an appliance will vary day-to-day and potentially seasonally. A single LED light, for example, might consume 5W when in use (e.g. in the evening) and 0W otherwise (e.g. during the day).

By adding together the demands for all appliances it is possible to produce the overall demand profile, a time series of energy demand over a given period (for example a day or year). The demand profile of a community of 100 households would be the sum of the profile for each individual household which, themselves, could each vary depending on their individual electricity uses or Tiers (Few *et al.*, 2022).

A demand profile can also be characterised in terms of the end uses of the electricity: the domestic demand profile for a community could include all demand profiles from households, whilst the commercial (or productive uses) profile would consider all demand profiles from businesses or agricultural activities. Typically, the demand profile of a single business or agricultural use is higher than that of a single household, and a single community institution (such as a hospital) is higher still (Beath *et al.*, 2021). The composition of the overall demand profile, in terms of end uses, will therefore depend both on the type and level of electricity demand of each single user and the number of those users in the community.

The overall community demand profile is the sum of all these demand profiles together and contains information about the level of power needed to meet the needs of the community, and the times at which it occurs. This quantification forms the basis of the mini-grid system design process which evaluates the capacity of the technologies required to meet those needs. Figure 5.1 shows two example demand profiles for two different communities of 100 households, one rural and one peri-urban (Few *et al.*, 2022). The two communities are characterised by similar domestic uses, but different productive uses. The rural community is characterized by agricultural end uses, such as irrigation pumps and rise mills, whereas the peri-urban community by business and community end uses, such as tailor, hairdressers, bars or a mosque. This results in very different community demand profiles both in terms of magnitude (with higher the peak magnitude for rural community) and temporal distribution (which is further discussed in the next section).

Understanding the magnitude of the overall community electricity demand is important for optimal system sizing. An oversized system, which overestimated the community electricity demand, would have more capacity than necessary to meet the actual demand. This can lead to increased costs of installation, operation, and maintenance, which could make it financially unsustainable or unaffordable for end users. Similarly, an oversized system could also lead to higher than necessary GHG emissions from those embedded in the system equipment, described in Section 3.

Conversely, underestimating the community electricity demand could lead to the system being undersized. This could lead to a lower reliability than expected by the system designer and potentially lower reliability than that promised to a community, manifesting itself as community members being unable to use appliances at certain times. This shortfall in the system's ability to provide electricity services to the community could reduce trust in the system and potentially leading to customers to abandon it completely (Lhendup, 2008; Shyu, 2013). A system that is designed accurately, according to the needs of community, should serve and fulfil those needs more consistently and will likely not be rejected or abandoned for these reasons (Feron, 2016).

Peak demand and daily energy use

Electricity demand is not uniform throughout the day as the demand for electricity services, and the power used by appliances that meet those needs, varies. The peak of the electricity demand is the period in the day when electricity use is the highest and, as a result of the variety in possible electricity end uses, the timing and magnitude of this peak varies between communities. The mean electricity demand is the average throughout the day, whilst the daily energy use is the total amount of energy consumed in an average 24-hour period. In real communities, there will likely be day-to-day and seasonal differences in the peak magnitude, timing, and overall electricity demand as demand for services and appliance usage varies (Williams *et al.*, 2017).

Figure 5.1 shows both the peak demand and the temporal variability for the two rural and peri-urban communities of 100 households (Few *et al.*, 2022). Firstly it shows how the peak demand is considerably higher for the rural community versus the peri-urban one, due to the high peak demand of agricultural productive uses (a rice mill and irrigation pump). Moreover, the two demand profiles differ in terms of temporal distribution. While the domestic demand (grey bars) has a similar profile in both communities (i.e. peak in the evening, with moderate demand in the early morning and low demand during the day) the productive end uses have significantly different temporal profiles. The commercial and productive users in peri urban community, plotted on top of the domestic demand, have relatively constant demand throughout the daytime and evening. These business demands are further composed of individual sources of load with different profiles: tailors have higher demand during the day, whereas hairdressers, bars and cinemas have higher demand in the evening. When combined, the overall community demand profile has a prominent evening peak, however the domestic and commercial demands in the early morning and daytime combine to a relatively consistent level of electricity demand.

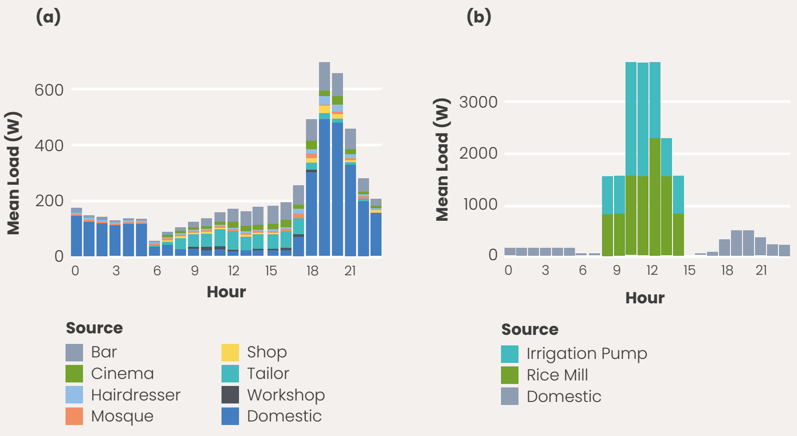


Figure 5.1. The hourly demand profiles of (a) peri-urban and (b) rural community with 100 households (Few *et al.*, 2022).

In contrast, the agricultural uses in the rural community lead to a high requirement for electricity during the middle of the day and none in the evening, resulting in a much less consistent level of demand over the day compared to the peri-urban case. These two demand profiles highlight both the potential differences in total electricity demand and timing of the peak demand in two communities of the same number of households, owing to their different uses of electricity services and locations, and can have significant implications on system design.

A high ratio of the peak demand to the mean demand for each day – potentially resulting from power spikes, for example from hospital equipment or heavy machinery – requires a mini-grid with equipment rated to provide high delivery power rating. Some of the components of a mini-grid are sized to meet peak demand rather than the average, for example the distribution network, the connection capacity to each consumer, the system protection equipment (such as circuit breakers), and the metering equipment. Any shortfall in delivery capacity can limit the peak power that can be provided and, if the peak demand is higher than the rated capacity, results in some demand going unmet at times of peak demand. This could incur higher system costs to pay for the more specialised equipment to meet that peak demand.

In contrast, the electricity generation and storage components of a mini-grid are usually sized to reliably meet daily energy use. A high variation in energy use within and between days could require a relatively large investment in generation, storage and/or backup generation equipment, depending on the reliability requirements of the system and the cost-effectiveness of the components. This is to meet demand on the days on which appliance usage is highest, and have higher-than-average load demands over the entire day, to avoid service being unavailable on these days. Any shortfall in generation or storage results in the mini-grid running out of energy before the end of the day, and either a complete loss of supply or energy rationing for some period of time will result.

Understanding and defining temporal distribution of demand

Accounting for timing of demand and variability

As described previously, electricity use in real communities can vary over several different timescales:

- Between hours, owing to when different electricity services are required (e.g. lighting at night – see also Figure 5.1);
- Between days, owing to random variations in when appliances in regular use are switched on or off (e.g. phone chargers being used at different times on different days), and between weekdays and weekends (e.g. for businesses);
- Between months or seasons, owing to variations in weather (e.g. affecting the use of fans or air conditioners) and agriculture patterns (e.g. higher demand for milling during harvesting seasons).

Furthermore changes in demand over shorter timescales, for example minutes or seconds as a result of individual appliances being switched on and off, can result in demand peaks presented in the previous section. These random variations can be more pronounced over shorter timescales, but are typically smoothed out by higher numbers of users in the community (see for example Figure 5.1 (a) discussed above).

In addition to the hourly variations in demand profiles previously shown, Figure 5.2 below gives an example of monthly variations in demand, based on the two example rural and peri-urban communities (Few *et al.*, 2022). Again, the magnitude of the demand differs between the communities and is much higher for the rural community with agricultural loads; furthermore, the rural community exhibits much higher demand from October to January owing to higher requirements for milling and irrigation. The domestic and business profiles, however, are relatively consistent throughout the year. The types of electricity services (for domestic, business, agricultural or other uses) can have a large impact on the timing and variability of demand, and hence the system design, its costs, and its GHG emissions.

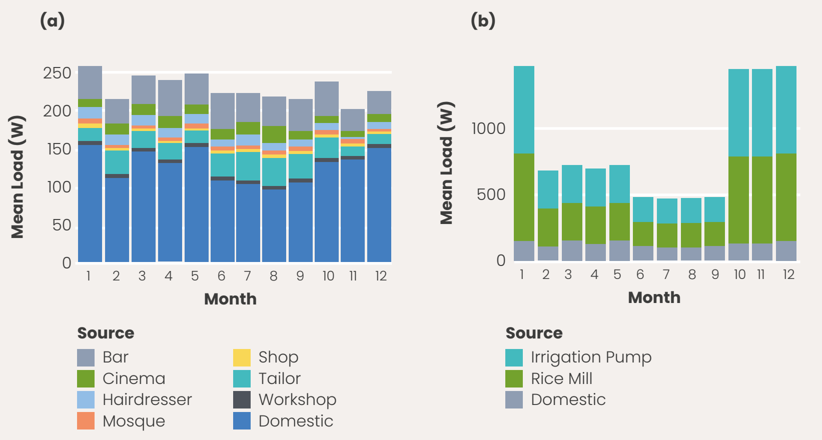


Figure 5.2. **The monthly energy demand of (a) a peri-urban and (b) a rural community with 100 households** (Few *et al.*, 2022).

In designing a mini-grids, the portion of electricity demand that coincides with renewable energy generation can be met relatively cheaply and easily, whereas demand at any other time requires some degree of energy storage or backup generation. In a mini-grid supplied primarily by solar PV, daytime demand can be met more easily than evening or night-time demand. This impact will be exacerbated in regions in which solar resource varies more throughout the year (for example from rainy seasons or in high latitudes) and, additionally, where lower generation coincides with higher demand for high-power agriculture processing. Similarly, variations in supply or demand associated with day of the week, holidays and festivals, short-term or seasonal weather patterns also affect the operation of a mini-grid.

Higher demand in the evening, overnight or in low-generation months can increase the storage requirements and therefore costs and GHG emissions of the system. Energy storage is more cost-effective when it is used more frequently to supply power rather than, for example, storing electricity for long periods of time. Longer battery cycles result in fewer cycles per unit of time; these are more costly compared to batteries which support energy provision for short-term day-to-day variation (Barton and Infield, 2004). Alternatively, demand which is temporally mismatched from renewable generation can be met instead by dispatchable backup generation, such as via diesel generators. The greater the mismatch, the more fuel is used with associated costs and GHG emissions.

Predictability and demand flexibility

In addition to estimating the overall magnitude and timing of the electricity services required by a community, it is also valuable to be able to foresee when demand might be higher and, if necessary, act if the energy supply will be insufficient to meet it. At the appliance level, some types of demand are more predictable and their electricity requirements can be estimated ahead of time (for example the overall usage of household lighting). Others may have unpredictable, short and high-power periods which are harder to predict, such as X-ray machines in hospitals (Beath *et al.*, 2021). Longer periods of higher overall demand could be the result of unpredictable weather patterns (for example unseasonably hot weather causing higher demand for fans and cooling) or other events (such as holidays resulting in higher demand for entertainment, but potentially lower demand for crop processing).

Predictability of demand and electricity supply are extremely important to the operation of hybrid mini-grids when dispatch decisions, for example whether to switch on a diesel generator, are made. These could include whether a mini-grid operator uses backup generation to charge the energy storage in anticipation of a spike in demand, or a potential future shortfall in supply. In both fully renewable and hybrid mini-grids, if two forms of energy storage are available then an operator could send surplus power to a longer-term store so that there is spare capacity in the shorter-term store, ready to accommodate a midday peak of solar power (BOS AG, 2017). These decisions benefit from predictions of both supply and demand based on previous experience and weather forecasting. Any uncertainty about the forecast results in more cautious decisions, usually resulting in less efficient operation, energy being wasted, or more fuel being burned by backup generation.

Both these situations are to be avoided, if possible. Some demands are flexible, meaning that an electricity service could be used at a different time with limited impact on the user. Charging a phone, for example, could be a flexible demand if it were to receive the required number of charging hours within a given window and is ready when a user needs it – such as three hours of charging at any point throughout a night, and is fully charged in the morning. Some demands are not flexible, such as lighting in a home: a user requires lighting to see at a specific time in a specific place, and if this service is not available then the value of this service is lost.

Identifying flexible demands, and moving them throughout the day, can help to flatten the demand curve and avoid power peaks or shortfalls in service. Aside from a system operator controlling when a community can use certain appliances, this can also be achieved by price-based (Zhong *et al.*, 2015; Muratori and Rizzoni, 2016; De Paola, Angeli and Strbac, 2017) or incentive-based (Zhong, Xie and Xia, 2013) demand response (DR) programmes. Apart from financial incentives, some end-users may be interested in ecological aspects of DR, such as the reduction of GHG emissions. End-users can also be incentivised for efficiency or curtailment behaviour (van der Werff, Thogersen and de Bruin, 2018).

System operators can implement DR programmes to help bridge the gap between electricity demand and supply, either regularly to incentivise the use of electricity services at certain times or to maintain the provision of power during periods of high demand and low supply. Well-designed systems can match supply and demand, potentially supported by DR, to reduce inefficiencies which could drive up prices and decrease the overall affordability of last-mile mini-grids.

Affordability and capacity building to support demand

Electricity from a solar mini-grid must be affordable to the local community in order for it to be accessible. Whether or not electricity is affordable will be related to:

- The ability to pay of a customer (whether they have the funds to pay for electricity at a given price),
- Their willingness to pay (if they have the funds, whether they would choose to spend them on electricity at that price).

The latter is also related to the price being charged for electricity services being offered, for example the tariff per kWh or per day, or for specific hours of usage for individual appliances (or combinations thereof) (ESMAP, 2019). Mini-grid operators might choose to offer consumers one or a choice of tariffs, often based on different levels of service or consumption. They could, for example, charge businesses higher tariffs: these users typically consume more electricity and have both a higher ability and willingness to pay, as a result of their income and to support their continued operations respectively.

Ensuring that the consumers can afford and are willing to pay for the electricity provided is central in determining the overall viability of a mini-grid. As discussed in Section 3, the LCOE – the minimum viable selling price for electricity – is calculated by the total costs of the system (equipment, maintenance, soft costs, and others) and the total amount of electricity provided. Whilst most of the capital costs are invested at the initial implementation of the system, during its long-term operation it is critical to ensure that the initially-projected amount of energy is sold in reality.

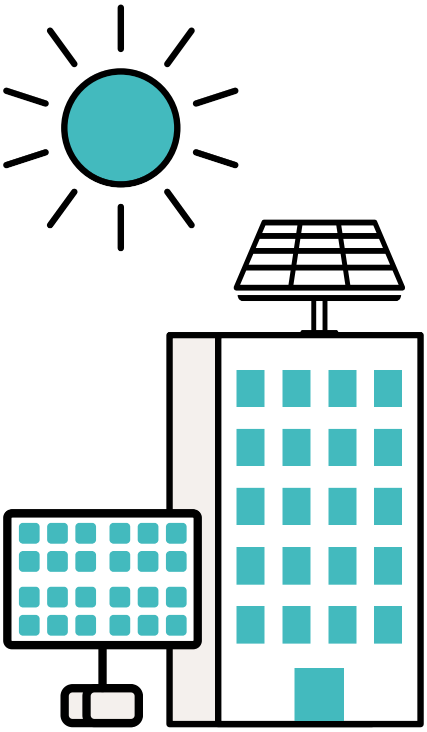
If electricity demand is too small, or if too few customers connect to the system, then the revenue of the mini-grid will be insufficient to recoup the initial investment or ongoing maintenance of the system. This may occur because users genuinely do not need or want to use more electricity (for example from an overestimation of demand) or, more often, because the users either cannot afford the electricity bills or do not consider worthwhile the electricity services being offered.

One solution is to stimulate demand (McCall and Santana, 2018): extensive efforts were made to promote electricity use in the early days of the electricity industry in now-developed countries. Stimulating demand via new connections to a solar mini-grid could increase the overall number of households in a community with electricity access; doing so via increased electricity use for existing customers, meanwhile, could increase their Tier of access. Catalysing or supporting productive uses of electricity can also increase community electricity use, promoting sustainable development for the community overall (Bisaga and Parikh, 2018; Riva *et al.*, 2018, 2019; Dominguez, Orehounig and Carmeliet, 2021).

Growth in demand over time

Electricity demand is not static. Populations grow and, more importantly, electricity demand grows as people are able to buy new appliances and appreciate the benefits that electricity access brings. As presented in Section 1 and Box 5.1 below, households and communities can move up through the Multi-Tier Framework (MTF) Tiers of electricity access. Transitioning from access to the most basic electricity services with the lowest electricity requirements to the higher Tiers with higher-capacity appliances and longer durations significantly increases the amount of electricity being used (Few *et al.*, 2022).

This growth in demand is strongly correlated with increasing economic prosperity, although many other complex community and social factors play a role (Riva *et al.*, 2018). Electricity demand in India has grown rapidly over time (Gaur *et al.*, 2016) and is expected to continue to grow with increasing appliance ownership and use (Rogers, 2008; Tiewsoh, Jirásek and Sivek, 2019; Poblete-Cazenave and Pachauri, 2021). As communities develop, and as more businesses and community facilities are founded and begin to use electricity (and themselves begin to use more over time) the overall electricity demand of the community can increase.



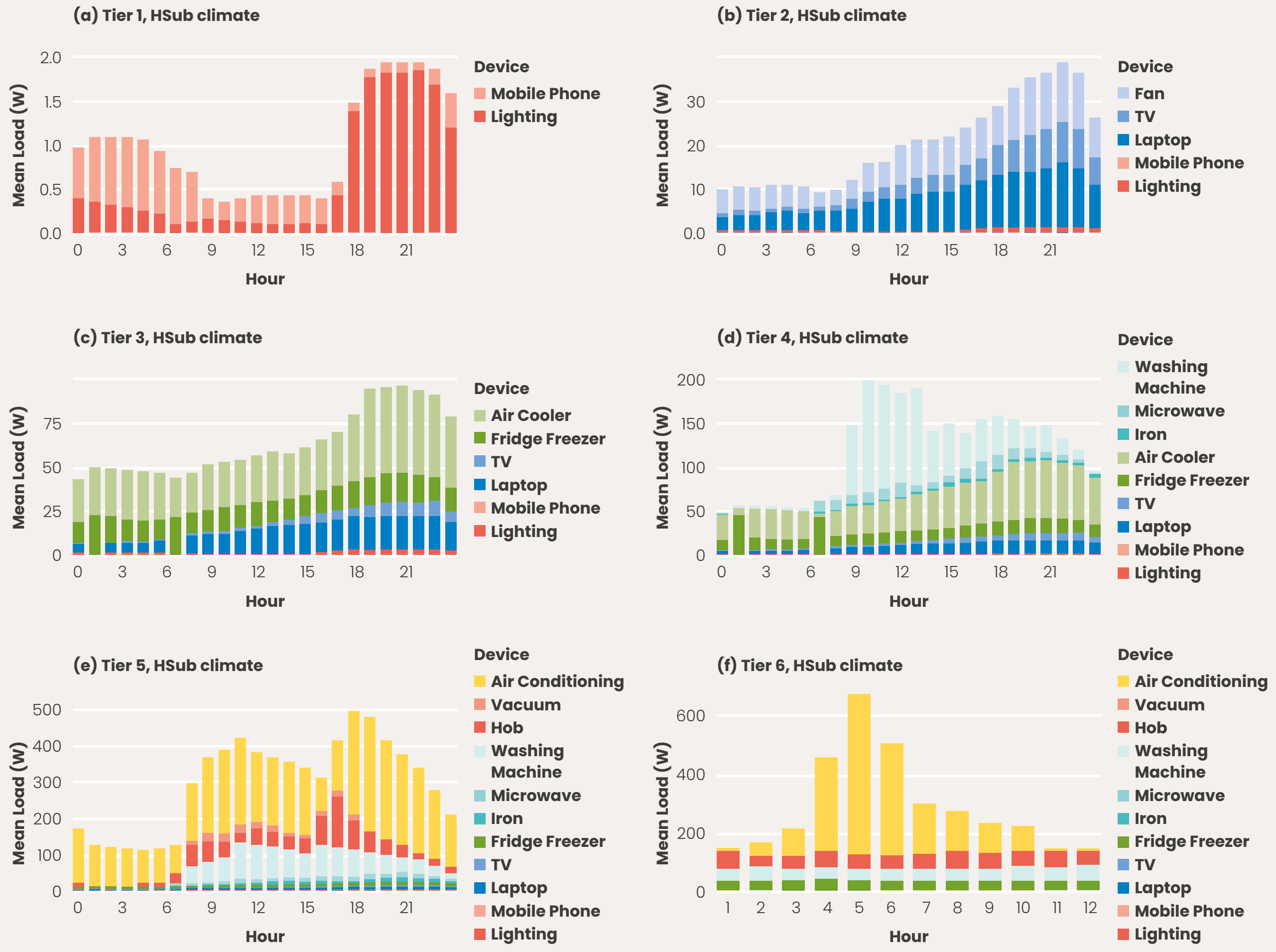
Box 5.1: The technical definitions of the Multi-Tier Framework

The Multi-Tier Framework (MTF) (Bhatia and Angelou, 2015) categorises seven attributes of energy access (capacity, duration, reliability, quality, affordability, legality, and health and safety) across six levels, from Tier 0 (no or extremely limited access to energy) to Tier 5 (full access to high-quality energy services). The goal of the MTF is to better categorise and quantify the attributes of electricity provision, as opposed to a simple consideration of whether or not a user has an electricity connection. Whilst a household, for example, could reach different Tiers for different criteria – such as a low-capacity connection (e.g. 3 W, Tier 1) but available for a long duration (e.g. 12 hours per day, Tier 3) – these are consolidated into a single Tier, the lowest in any single criterion. As the Tier increases, generally so too does the overall capacity and duration – and hence total energy use – of the household or community.

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	Power		Very Low Power Min 3W	Low Power Min 50W	Medium Power Min 200W	High Power Min 800W	Very High Power Min 2KW
	AND Daily Capacity		Min 12Wh	Min 200Wh	Min 1.0KWh	Min 3.4KWh	Min 8.2KWh
	OR Services		Lighting of 1,000 ohms per day and phone charging	Electrical lightimg, air circulation, television and phone charging are possible			
2. Duration	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration
4. Quality						Voltage problems do not affect the use of desired appliance	
5. Affordability					Cost of a standard consumption package of 365KWh per annum is less than 5% of household income		
6. Legality					Bill is paid to the utility prepaid card seller, or authorised representative		
7. Health and Safety					Absence of past accidents and perception of high risk in the future		

Figure 5.3. The Multi-Tier framework for household electricity supply, from Bhatia and Angelou (2015).

Some of this demand growth can be explored through comparisons between rural and urban locations. Electricity demand in India is lower in rural locations than urban and it is predicted to remain so for many years to come (Rogers, 2008; Poblete-Cazenave and Pachauri, 2021). This difference is generally due to lower levels of economic development in rural locations, but the level of development is expected to increase over time – and with it, bring increasing levels of electricity demand.



(a) Tier 1, HSub climate

(b) Tier 2, HSub climate

(c) Tier 3, HSub climate

(d) Tier 4, HSub climate

(e) Tier 5, HSub climate

(f) Tier 6, HSub climate

Figure 5.4. Mean hourly demand by device for a simulated household in energy access tiers 1-5 in a humid subtropical climate (f) mean monthly demand by device for a simulated household in energy access in a humid subtropical climate.

The type of appliances owned and used is also different between urban and rural locations: urban households are more likely to use higher-power electronics, electric cooking devices (both because of restrictions on the use of open fires but also because biomass fuels are more expensive or less available), and air conditioning or other cooling devices (both because the building construction is more prone to overheating but also to overcome the heat island effect of towns and cities). Meanwhile, rural households are more likely to use electrical machines for agricultural purposes and basic food processing such as milling. As the overall level of electricity access and economic development in rural areas begins to match that of urban areas, the sources of that electricity – such as solar mini-grids – will need to reliably supply those increased levels of power demand.

Figure 5.4 demonstrates how the Tier of electricity access of a household can significantly affect its overall demand for electricity (Few *et al.*, 2022). As the number and usage of appliances grows in the example household, the magnitude of the peak demand increase (from just a few Watts for Tier 1 to several hundred Watts for Tier 5) and the shape of that peak changes (peaking in the evening, and throughout the day and evening respectively). Combined with the varying demand for cooling throughout the year shown in Figure 5.4 (f), and multiplied across an entire community of households, the increase in Tiers over time highlights the impacts and importance of considering demand growth over time.

As shown in Figure 5.4, Tiers 1-3 have highest demand in the evening which does not match solar generation well; Tiers 4 and 5, however, have high demand for cooling which better matches the solar profile (Few *et al.*, 2022). This could benefit the inherent design advantages of solar mini-grids, to meet demand during the daytime, and support their use for higher-Tier applications. Depending on the specific situation of the community it may be, however, that providing levels of electricity service to Tier 5 remains the domain of traditional grid connections (Bhatia and Angelou, 2015).

To accommodate this growing demand, mini-grids need some headroom of generating capacity to accommodate future growth in their initial design and construction, and should also be easily expandable. This increase in capacity to meet a growing demand may be achieved by building mini-grids using modular components that can be bolted on to an existing system in a “plug-and-play” mode, with minimal cost or disruption in service to the community. Understanding how communities will use electricity, how this will grow over time, and how to design systems to support this are therefore inherently important in supporting sustainable development.

5.3. ESTIMATING DEMAND: METHODS AND MODELLING

The quantification of demand estimation has been the subject of much research. Inherent issues such as the specific needs and priorities of individuals and communities, variations between communities even in similar locations, and the effectiveness of approaches presented here in reflecting real-life electricity use remain challenging to overcome but, through modelling and assessments, implementers can attempt to better predict community electricity demand (Blodgett *et al.*, 2017; Hartvigsson and Ahlgren, 2018).

The demand profile can be obtained or predicted using the data from customer surveys, from monitoring devices such as smart meters, or reconstructed, for example according to monthly energy consumption and a typical load profile of the end users. This can also potentially be further broken down by classifying consumers according to their typical energy needs and usage (Gerbec, Gasperic and Gubina, 2003). A probabilistic approach can be applied if limited statistical data exist to generate the profile of a group of users at the desired aggregation level relying on, for example using a log-normal or gamma distribution (Carpaneto and Chicco, 2008). Similarly to the demand profile, demand flexibility can be assessed using smart meter data (Ponoćko and Milanović, 2018), clustering techniques (Kang *et al.*, 2018) or probabilistically (Sajjad, Chicco and Napoli, 2016).

Data collected by mini-grid providers may be used to better understand real-world demand profiles. Monitoring existing electricity systems, such as previously installed mini-grids or even individual appliances, can provide estimates for the design of future systems (Louie and Dauenhauer, 2016; Hartvigsson and Ahlgren, 2018). Metering equipment can measure the electricity usage of a community over a period of time and this data can be processed to quantify the means and variations in hourly electricity demand. This is advantageous as it allows the input real electricity usage in system design and can provide a more realistic representation of demand; on the other hand, a system designer would need to be confident that the monitored usage accurately reflects the anticipated usage in the new community. Furthermore, the acquisition of monitored data can be a complex process, both owing to the logistics and timescales required to install meters and record information and potential privacy concerns about the data. National demand patterns are also useful in the absence of local data (Gerbec, Gasperic and Gubina, 2003; Gaur *et al.*, 2016).

An alternative is to build demand profiles from the bottom up based on literature, community surveys, or assumptions about energy demand. Current and aspirational demand has in some cases been quantified prior to mini-grid development through a survey-based approach (Sandwell, Chambon, *et al.*, 2016). There are many ways of predicting electricity demand in this manner, but many rely on input data about the expected number of appliances in a community, the probability that an appliance is in use at a given time, and the power ratings of devices (Sandwell, Chambon, *et al.*, 2016; Riva *et al.*, 2019; Stevanato *et al.*, 2020). Some, such as the CREST demand model developed at Loughborough University (McKenna, Thomson and Barton, 2015; Barton *et al.*, 2020), use more detailed processes such as building occupancy or weather data to predict appliance usage and can use statistics to randomise the load to replicate day-to-day variations.

Synthesising electricity profiles in this manner can give more control over the practicalities of demand, for example by first defining the demands for a service (such as lighting) before considering the resultant energy demand of an appliance that provides that service (such as high-efficiency LEDs or low-efficiency incandescent bulbs). This process is also generally more customisable as the system designer can configure a wide range of parameters to define the load of the community, and it can also be used to assess how demand might grow over time (see Box 5.2). On the other hand, these approaches are inherently dependent on the quality of the data or assumptions used in building the load profile, literature data may not be reflective of the situation a mini-grid is being designed for, and directly surveying the prospective users of a system can be challenging. Furthermore, the variability of real electricity demand between households is also often greater than modelled or expected (Ramírez-Mendiola, Grünewald and Eyre, 2017) with discrepancies between estimations and reality attributed to factors such as difference in appliance ownership rates, power ratings, and times of usage (Few *et al.*, 2022).

Load estimation should incorporate socio-economic and gender aspects to obtain a better estimation of the load demand. Gender roles within the community significantly affect the choice of appliances and time of use both in the households and community projects (Namaganda-Kiyimba and Mutale, 2020). Gender considerations could include whether men and women identify different electricity needs or priorities in the community, who has control over a household's assets and financial decision making (with regards to paying for different electricity services), gender distribution of the roles in the management of community projects, and any cultural norms or constraints.

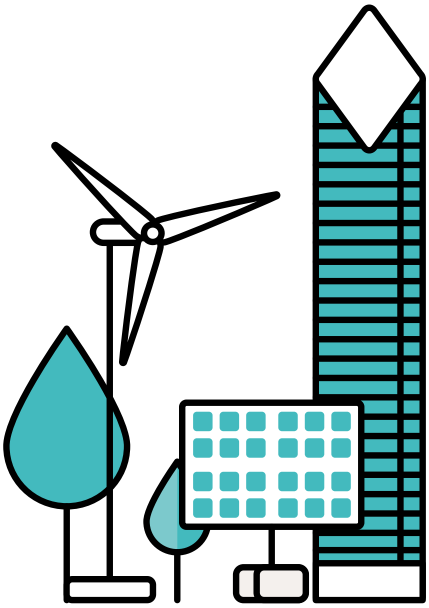
BOX 5.2: FLEXIBLE LOADS AND THE TIERS OF ENERGY ACCESS

As the electricity demands of a community grow, so too do the opportunities for flexibility in meeting them. At Tier 0 or 1 of the MTF electricity demands are relatively time-dependent – the value of simple electric lighting, for example, is mostly reliant on being available when needed at night. At higher Tiers, however, loads can be shifted with greater ease: usage of a washing machine, for example, could be shifted to the middle of the day to coincide with higher solar generation with much less impact on the consumer. Furthermore, when a mini-grid supplies non-domestic loads, the range of potential flexible loads is much wider (Element Energy and De Montfort University, 2012; McKenna, Doylend and Thomson, 2013; Gils, 2014).

At Tier 5, air conditioning is a key flexible load, for example in the Indian context (Ershad *et al.*, 2020). Large refrigeration and freezer facilities, which could for example be used to store agricultural produce in rural areas, contain a large thermal mass and therefore offer another significant flexible load (Short, Infield and Freris, 2007; Wai *et al.*, 2015; Morales González *et al.*, 2018). In the future electric vehicle (EV) charging could represent another flexible load, given the large batteries in EVs and the large proportion of time they spend stationary, but their uptake in rural areas remains to be seen.

As solar mini-grids grow in their application and diversity – from supplying basic levels of electricity, to reaching the higher Tiers of the MTF – the opportunities for demand response and other control opportunities will grow. So too could the necessity to do so as mini-grids move towards more financially sustainable models for operators and, with it, the need to find operational and economic efficiencies whilst continuing to supply reliable power in remote and rural areas of India equivalent to those in urban centres.

This section has highlighted the importance of understanding community electricity demand before a solar mini-grid system is deployed but, even with confidence of the ability of a designed system in meeting that demand, many more challenges emerge during implementation. The most effective business model for the operator, the ability of a system to meet the constraints of a community – particularly regarding affordability – and the potential to integrate local management and ownership are each critical considerations in real-life deployment. The following section explores these challenges and opportunities for solar mini-grids in India.



6. THE CASE FOR SOLAR MINI-GRIDS IN INDIA

Deployment of solar mini-grid systems for last-mile electrification can be supported by effective system design, technological improvements and cost reductions, and improved understanding of the demand for electricity services by rural communities. The implementation of mini-grids in rural India will further require effective delivery models and community engagement to overcome affordability, financial, and regulatory challenges.

- Subsidised tariffs of the grid network can make cost-reflective mini-grid tariffs unaffordable in comparison and inhibits mini-grid deployment. Anchor loads, cross-subsidisation and different tariffs for different users could help to overcome this.
- Solar mini-grids can provide more reliable power, which is critically important for productive and community services, and their ability to meet (and promote) growing demand over time could increase their potential benefits for last-mile communities.
- There are a variety of operation and ownership models with different roles for mini-grid companies, communities, NGOs, and government actors, but meaningful involvement and engagement by the community is critical in long-term success.
- Several challenges remain for a successful scale-up of mini-grids, but a more supportive enabling environment could be created through both policy and regulatory frameworks, and through careful analysis and support given to evolving implementation models.

6.1. DEPLOYING SOLAR MINI-GRIDS IN INDIA

For the challenge of last mile electrification, solar mini-grids are an increasingly viable option to provide affordable, sustainable, reliable and modern electricity services to unelectrified or partially electrified communities. In rural and remote areas not served by the grid they can be the most cost-effective option for electricity supply and more sustainable than traditional means of electrification. Recent and prospective technology developments in system components, such as PV modules and storage solutions (Section 4), are likely to progressively reduce investment costs and improve mini-grid cost competitiveness versus other electrification solutions, including grid extension, particularly in remote areas (ESMAP, 2019).

If well designed and implemented (Section 3) solar mini-grids can provide reliable power to unelectrified communities, as well as to partially electrified ones by providing power when grid electricity is unavailable. Good design and, within that, a robust characterisation and estimation of current and prospective demand (Section 5) is crucial in order for a mini-grid to successfully meet the needs of the community that it serves.

When human development and economic growth are factored in, mini-grids allow the opportunity to move beyond providing a lifeline via basic electricity services and toward supporting wider community-level activities and socio-economic benefits. Thanks to their higher-capacity power compared to other renewable off-grid solutions (such as solar home systems or solar lamps), they can not only supply household-level end uses but also productive uses to power small businesses and enable increased local incomes, and additionally support community services such as for healthcare and education.

To capitalise on their potential to provide last mile electrification, mini-grids must have effective financial and implementation models to meet the needs of communities in the real world. Customers, system operators, governments, and other stakeholders each have their own needs, objectives and constraints, and this section discusses the issues in balancing these as part of an effective long-term deployment strategy.

6.2. OVERCOMING FINANCIAL BARRIERS

Providing affordable electricity to customers

Affordability is one of the major reported causes for Indian households not having a connection (Agrawal *et al.*, 2020). Indeed, providing the final user with affordable electricity is one of the essential attributes of electricity provision, particularly for low-income households. Investing in the least-cost option to generate electricity (lowest LCOE – see Section 3.3) is an important prerequisite. Generally, mini-grids tend to be more cost-effective than grid extension in locations distant from the grid and in remote communities (Section 1.3). However in India the grid has already reached the vast majority of communities (Indian Ministry of Power, 2021), thus making the generation cost of mini-grids less competitive. Moreover, due to high taxes on critical renewable energy components, the investment costs (CAPEX) of mini-grids can be high. This can make them a less attractive investment, in particular for mini-grid companies which tend to be small and undercapitalised (Section 2.3). The economics of mini-grids in India, in the absence of government support or international donors covering the upfront capital cost, would therefore not currently make mini-grid a cost-effective option.

In addition, affordability of electricity provision for the customer depends not only on the generation cost of the technology and system chosen, but also on the supply tariff charged, which depends on market and policy factors. In India the grid is highly subsidised and, with relatively little practical Government funding for mini-grids (Comello *et al.*, 2017), this makes grid tariffs cheaper than cost-reflective mini-grid tariffs. When available, this subsidisation leads to grid electricity tending to be more affordable than that which a mini-grid could provide. While cheaper tariffs from grid would ease the cost barriers for end users, they can also discourage investment in the mini-grid sector in communities where the two electrification options would compete. A possible solution is to encourage mini-grid deployment by in¬cluding cross-subsidies based on customer classes or setting differential tariff levels based on mini-grid size and capacity (Reber *et al.*, 2018).

Mini-grid financial models and challenges

Affordability and the inability of a households to pay the monthly bill is not only a barrier to electricity access, but also a critical element in supporting the financial sustainability of mini-grid investments. In India revenue collection is commonly perceived as a challenge for mini-grid operators (Jaffer, 2016; Power for All, 2018) which have explored new ways to secure stable revenue streams. Many mini-grid operators collect payments from customers with field collection agents; some are implementing different payment collec¬tion models, such as group payment collection (where the field agent comes to a group meeting where everyone pays together), mobile payment systems, or pay-as-you-go systems (Power for All, 2018; Sustainable Energy for All and Bloomberg NEF, 2020b).

Another financial risk for Indian mini-grid operators is the viability of their investment if the main grid is extended to their area of operation. Customers switching from using the mini-grid to using the grid instead, perhaps motivated by its subsidised costs, could therefore create a huge loss of income for the mini-grid investors. No regulatory framework in India specifies what is to happen if the central grid were extended to an area already covered by a mini-grid (Sections 2.3 and 4.6). Options for co-existence of operation of mini-grids with the grid do exist, but these involve technical (Section 4.6), market and regulatory challenges (Comello *et al.*, 2017; Sustainable Energy for All and Bloomberg NEF, 2020a, 2020b).

A successful financial model for mini-grid operators is the Business to Business (B2B) and Business to Customer (B2C) model, in which mini-grids sell to both businesses and residential consumers. This involves looking for an “anchor load” as a system design solution in order to guarantee a constant demand for the mini-grid system and, in turn, support the financial viability of the investment (Beath *et al.*, 2021). In the context of the last mile electrification, anchor loads could be productive uses in agriculture, such as water pumps and agricultural facilities, as well as commercial loads from small businesses or telecom towers, ATMs and petrol pumps. These customers have both larger and more predictable demand than residential customers, which could guarantee a more predictable load and a more secure stream of revenues over time. Differentiating consumers by type also allows mini-grid operators to apply different tariffs in order to optimise revenue generation. Larger anchor loads tend to be charged by mini-grid operators on a per-unit-of-consumption basis, while smaller residential consumers are charged a flat tariff (for example per day or month) eliminating the need for installing meters at their premises and hence reducing costs. Moreover, designing a system with an anchor load can also help in maintaining a stable electricity demand to be served by the mini-grid system, even when the central grid arrives.

For example, Tara Urja, an Indian non-profit organisation seeking to promote rural development through electrification in India, deploys mini-grid with a model in which sustainability depends upon a mix of varied residential and community loads and a few mini-anchor loads. In association with Smart Power India, they have installed several solar mini-grid systems with a water treatment unit associated as a mini-anchor (Mohapatra, Jaeger and Wiemann, 2019). Supporting the growth of communities' electricity demand over time (Section 5.2), in addition to being a crucial element for their socio-economic development as discussed below, it is also a strategy to guarantee a more stable source of revenues and improve the financial viability of mini-grid systems.

6.3. SUPPORTING COMMUNITY DEVELOPMENT

Solar mini-grids can both provide a solution to provide first access to electricity in India's rural communities, and improve the quality of electricity provision in those which are partially electrified. Despite India's success in improving access to electricity, and the Government announcement of having achieved full electricity access with 99.99% of Indian villages electrified, there remains significant gaps in the country in terms of clean, reliable and modern electricity provision, particularly in rural areas and for low-income households and small businesses (Section 2). The definition of a "fully electrified" village – when 10% of the households have an electricity connection (Basumatary, 2021) – implies that many households and businesses in these communities remain unelectrified. Indeed, the majority of the unelectrified population in India is reported to live in rural areas, particularly in the states of Uttar Pradesh, Madhya Pradesh, Rajasthan, and Bihar. Improving electricity access in these areas will be critical in meeting full electricity access in the country.

Providing reliable and modern electricity services

Despite affordability and financial challenges, mini-grids in India can be a viable option to improve reliability of the electricity service. In India, two thirds of the electrified rural population face outages at least once a day. It is estimated that the 96.7% of Indian households electrified via the grid receive an average of 20.6 hours of electricity per day, but this goes down to only 18.5 hours a day in the more rural north-central states of India (Agrawal *et al.*, 2020). Reliability of electricity provision is particularly important for rural productive activities, such as milling, processing and refrigeration for food products, as the lack of reliable power can hinder their operation as well as their growth and further development (Power for All, 2020).

In some regions of India small rural business do rely on solar mini-grids for electricity provision, rather than the grid: in Uttar Pradesh, for example, around 32% of small businesses rely on only solar mini-grids. Moreover, 18% and 32% of people in Uttar Pradesh and Bihar respectively use off-grid technologies in conjunction with the grid to bridge the 9-12 hours of power failure in each day (Sustainable Energy for All and Bloomberg NEF, 2020b).

The ability of mini-grids to provide reliable power is valued by final customers, which have been found to be willing to pay higher mini-grid tariffs in exchange of greater reliability of supply (Okapi Research and Advisory, 2017). Moreover, evidence also has shown that reliability of provision can support the coexistence of mini-grids with the grid upon its arrival. For instance, in the town of Pipra Kothi customers served by an hybrid biomass and solar mini-grid opted to stay with the mini-grid when the distribution grid has expanded to the site, primarily because they have valued the more reliable electricity provided (Sustainable Energy for All and Bloomberg NEF, 2020a).

Facilitating growth in electricity services

Another important attribute of mini-grids is their ability to supply modern electricity services (Section 1.1) to serve multiple end uses and to support increasing levels of demand over time, thus contributing to the primary objective of electricity access: socio-economic development. Thanks to their higher-capacity power compared to other off grid they can provide electricity not only for households needs, but also to productive and income-generating activities (Ganguly *et al.*, 2020; Hartvigsson *et al.*, 2021), such as machinery, agro-processing equipment and refrigeration, and community services, such as schools or health clinics.

As communities develop, they can reach higher levels of the Multi-Tier Framework (MTF) (Box 1.1), transitioning from access to the most basic electricity services with the lowest electricity requirements to higher Tiers with higher-capacity appliances and additional productive and community uses (Section 5.2). This growth and diversification of end uses implies significant increases in the amount of electricity being used (Few *et al.*, 2022), a growing trend already experienced in India (Gaur *et al.*, 2016) and expected to continue over time (Rogers, 2008; Tiewsoh, Jirásek and Sivek, 2019; Poblete-Cazenave and Pachauri, 2021). Compared to other off-grid, low carbon solutions, mini-grids can supply higher levels of electricity demand and, as such, support wider socio-economic benefits and development (Section 1.2).

In order to be able to supply high and growing community needs, mini-grids design should account for a robust characterisation of demand of the end uses that the system is going to serve (Section 5). This should encompass both a good estimation of the present needs of the community as well as their grow over time. Overestimating demand would imply a system oversized for the community needs, with higher generation costs which could reduce the financial viability of the system. On the contrary, underestimating demand could result in the inability of the system to provide the needed electricity services of the community, hence reducing customers satisfaction and trust, and potentially result in abandonment. If few customers are connected to the system or if their demand is too small, then the revenue of the mini-grid will likely be insufficient to recoup the initial investment or ongoing maintenance of the system. Hence, meeting the needs of a community and support their evolution over time is a crucial element in mini-grids' electricity provision as well as in supporting their financial viability, as also discussed above.

Indeed, some mini-grid developers implement business models which, along with mini-grids deployment, also aim to stimulate communities' demand. Increased demand would provide additional revenue streams for developers, while also promoting the development of the served communities, which would move up the Tiers of access via increased opportunities of electricity use. An example is Mlinda, an Indian NGO which implements low carbon projects in highly underdeveloped areas. They evolved their rural electrification activities toward mini-grids in order to provide access to reliable electricity for household and to serve aspirational community needs. In Sahitoli, a tribal village in Gumla district, they implemented a 22.4 kWp solar mini-grid, which was made financially sustainable at the village level by reaching 95% of capacity utilisation over a period of 30 months. They provided loans to farmers to finance energy efficient devices to accelerate uptake, and supported conversion from diesel power to mini-grid electricity of existing agri-business appliances, such as rice hullers and wheat mills. They also supported the development of new agri-business activities such as oil expelling. The mini-grid serves 124 households and productive uses have been increasing month by month, including 19 small pumps, three rise hullers, two wheat mills and two shops in the village (Sustainable Energy for All and Bloomberg NEF, 2020a).

Ownership and operation models for community management and involvement

Mini-grid implementation models can take many forms, depending on which stakeholder owns and operates the mini-grid asset. In private operator models a private developer or the utility owns and operates the mini-grid. In hybrids models, different organisations may be in charge of ownership, generation and distribution, and projects which use hybrid models are often implemented under public-private partnerships. In community-based models it is the local community that owns and operate

the mini-grid (Sustainable Energy for All and Bloomberg NEF, 2020b).
In India private models vary, but the most common is the build-own-operate model, which allows control across the value chain. The build-operate-transfer model is less common as it can be difficult to find off-takers to own or operate the system. Also common in India are the community-based models, which are usually publicly supported and are structured around community entities such as Village Energy Committees (VEC) or Rural Electricity Cooperatives (REC) (Power for All, 2018).

Community involvement upfront, during system's design and installation, is deemed to empower local actors which become active stakeholders in the projects. This can increase satisfaction of end users (Evans and Birchenough, 2001), create a sense of ownership (Marks and Davis, 2012) and facilitate system's maintenance and longer-term functionality. Community engagement could also help in tailoring system design on community's present and future needs, resulting in improved characterisation of demand and system design (Sections 3 and 5), which would increase both cost-effectiveness and acceptance of the mini-grid. In practice, performance of community-level operation of mini-grids can be different across initiatives, often related to specific problems due to bottlenecks in local capacity and knowledge (Holstenkamp, 2019). In India community models have not always provided long-term sustainability, due to different failure in local institutional design, such us unclear definition of roles and responsibilities (Ulsrud *et al.*, 2011), or an inability to build local capacity (Palit *et al.*, 2013).

Nonetheless, involvement of the community is generally deemed to be an essential factor for the success of a project regardless of which business model is chosen (ESMAP, 2000). Recent research reviewed 24 community-based solar mini-grid systems installed in three different India states by Gram Oorja, a social enterprise operating in India (Katre, Tozzi and Bhattacharyya, 2019), with the aim of exploring factors affecting long-term sustainability and replicability of the models implemented. The mini-grid systems were designed to provide domestic uses, household commercial activities, public spaces and water for drinking purposes. The systems are community-owned and with a locally elected VEC responsible for daily technical and financial operations. The ownership of the asset is retained by the funder, with the ability to withdraw the asset if the plant becomes non-operational. The plants are financed with upfront capital provided to the community and through billing collected by a local plant operator.

Data collected using semi-structured interviews with VEC members and surveys with households and local operators allows a scoring of the mini-grid sites along several factors, including indicators of efficiency of governance and community satisfaction. The results show both high scores, and increasing levels of scoring over time, for indicators of community participation (Figure 6.1), user satisfaction and effectiveness of governance. The study also identified the ability to build local capacity in financial and technical management and effective local governance, as well as the increased level of community participation and involvement, as core features in the achievement of long-term sustainability of the mini-grid systems.

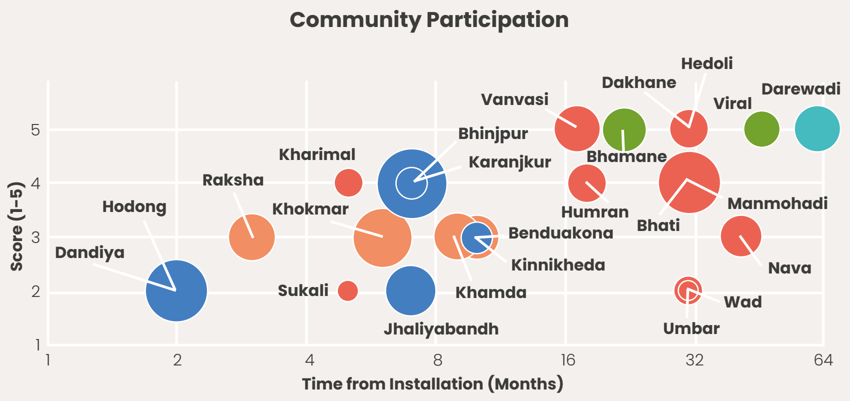


Figure 6.1. Scores for community participation amongst mini-grid projects, with scores generally increasing with time since installation (Katre, Tozzi and Bhattacharyya, 2019). The size of the circles is representative of the number of households connected to the mini-grid.

6.4. Supporting scale up implementation

Solar mini-grids have been implemented in India since the 1980s, supported by several national- and state-level policy support programmes, including the Saubhagya Scheme launched in 2017 with the aim of providing last-mile connectivity to unelectrified rural communities (Section 2). By 2019, almost 1,800 mini-grids had been implemented across India, with a concentration in the northern and eastern areas of the country. These are also the areas which host the majority of the rural population who are unelectrified or in need of a better-quality electricity provision (Section 2.2). However, these mini-grids have often been dysfunctional due to inefficient financial planning, a lack of local capabilities which could guarantee long-term performance and durability, or a poor understanding of and plan for communities' and stakeholders' needs and capacities.

More recently, mini-grids are increasingly seen as a ready-to-go solution to improve access to electricity in India, particularly in rural and remote communities. New investments, funding and promotion of mini-grids are coming along in India: international organisations and private corporations such as the Rockefeller Foundations and Tata Power have set targets for mini-grid implementation in India for the coming years, along with smaller developers and NGOs acting as rural energy service companies (Section 2.3).

However, several challenges remain for a successful scale-up implementation of mini-grids in India and a more favourable enabling environment could be created.

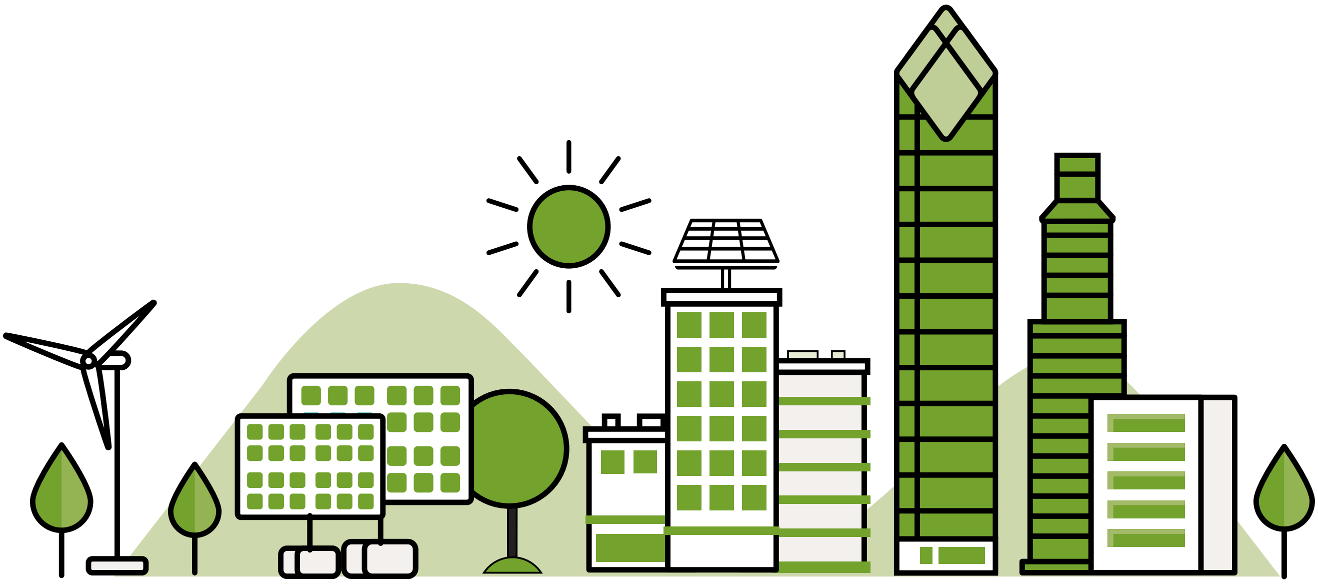
As discussed above, the high initial investment costs (exacerbated by high taxes on critical system components) coupled with subsidised tariffs for grid electricity tend to make mini-grids not cost-effective compared to the grid, and this affects the financial viability of investments in mini-grid systems. Mini-grid developers, which are often small and undercapitalised, find themselves in a challenging environment, struggling to access the capital necessary to build projects. Government-provided capital grants or international donors covering the upfront capital cost (or part of it) have been and could keep being suitable solutions to support the financial viability of mini-grid investments. Moreover, policies could also be set in place to improve access to finance for to mini-grid developers. For example, nationalised banks could be provisioned to provide long-term financing at lower interest rates (Jaffer, 2016).

The financial viability of investments in mini-grids is also challenged by revenue collection issues, due to a combination of affordability for the prospective end users and, more generally, poor management of the electricity services to date (e.g. a lack of metering and low rates of payment collection enforcement). As discussed above, mini-grid developers are implementing strategies in their business models to reduce risks associated with revenue collection. However, government support in introducing stricter policies (such as cutting off supply due to the non-payment of a monthly bill) could also help in creating a strong culture of regular payments amongst consumers (Section 2.3).

Improved policy and regulatory framework could also be implemented to facilitate the coexistence of mini-grids with the national grid. Investment in mini-grids can often be discouraged by the risk, real or perceived, of future extension of the grid to their areas of operation, which would affect their financial viability. Such risk could be mitigated with a clear regulatory framework defining conditions of integration and utilisation of the existing mini-grid infrastructure if the grid were to arrive. More generally, it looks relevant to consider the potential for mini-grids to act as a hybrid component of the grid, and not necessarily a supplement to the grid (Section 4.6), which can support utilities by providing locally-generated power supply to remote communities (Okapi Research and Advisory, 2017).

Besides issues surrounding affordability and financial viability of mini-grids investments, it is relevant to remember that the suitability of mini-grids as an electrification option in India also resides in their ability to offer faster connections, as well as improved opportunities for reliable electricity services and lower-carbon electricity compared to the national grid network. Moreover, they have the potential to support communities' development over time, thanks to their ability to power a range of domestic, productive and community applications.

Achieving SDG 7 in India will require a concerted approach and, in doing so, mini-grids can help facilitate not only the provision of basic electricity services, but also wider community-level activities and socio-economic development. To support successful deployment of mini-grids in the years to come further investigation and attention should also be given to business and implementation models, in order to guarantee both long-term sustainability of the models implemented and their ability to serve the present needs and future aspirations of communities in India.



7. BIBLIOGRAPHY

Adefarati, T. and Bansal, R. C. (2019) 'Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources', *Applied Energy*. Elsevier, 236, pp. 1089–1114. doi: 10.1016/J.APENERGY.2018.12.050.

Agrawal, S. *et al.* (2020) *State of Electricity Access in India: Insights from the India Residential Energy Survey (IRES 2020)*. New Delhi, India.

Akbas, B. *et al.* (2022) 'Rural electrification: An overview of optimization methods', *Renewable and Sustainable Energy Reviews*. Pergamon, 156, p. 111935. doi: 10.1016/J.RSER.2021.111935.

Amutha, W. M. and Rajini, V. (2016) 'Cost benefit and technical analysis of rural electrification alternatives in southern India using HOMER', *Renewable and Sustainable Energy Reviews*. Pergamon, 62, pp. 236–246. doi: 10.1016/J.RSER.2016.04.042.

Arranz-Piera, P. (2017) *Benchmarking Study of Solar PV Mini Grids Investment Costs*. Washington DC.

ARUP (2021) *Five minute guide to microgrids*. Available at: https://www.arup.com/perspectives/publications/promotional-materials/section/five-minute-guide-to-microgrids (Accessed: 1 February 2022).

Ashden (2011) *Husk Power Systems - Ashden*. Available at: https://ashden.org/winners/husk-power-systems/ (Accessed: 1 February 2022).

Babatunde, O. *et al.* (2018) 'Evaluation of a grid-independent solar photovoltaic system for primary health centres (PHCs) in developing countries', *Renewable Energy Focus*. Elsevier, 24, pp. 16–27. doi: 10.1016/J.REF.2017.10.005.

Bahramara, S., Moghaddam, M. P. and Haghifam, M. R. (2016) 'Optimal planning of hybrid renewable energy systems using HOMER: A review', *Renewable and Sustainable Energy Reviews*. Pergamon, 62, pp. 609–620. doi: 10.1016/J.RSER.2016.05.039.

Banerjee, S. G. *et al.* (2015) *Power for All: Electricity Access Challenge in India*. Washington DC. Available at: http://hdl.handle.net/10986/20525.

Baranda Alonso, J., Sandwell, P. and Nelson, J. (2021) 'The potential for solar-diesel hybrid mini-grids in refugee camps: A case study of Nyabiheke camp, Rwanda', *Sustainable Energy Technologies and Assessments*. Elsevier, 44, p. 101095. doi: 10.1016/J.SETA.2021.101095.

Barton, J. *et al.* (2020) 'A Domestic Demand Model for India', in Singh, S. and Ramadesigan, V. (eds) Advances in *Energy Research*, Vol. 1. Singapore: Springer Singapore, pp. 743–753.

Barton, J. P. and Infield, D. G. (2004) 'Energy storage and its use with intermittent renewable energy', *IEEE Transactions on Energy Conversion*, 19(2), pp. 441–448. doi: 10.1109/TEC.2003.822305.

Basumatary, S. (2021) 'The myth and reality of electricity connection in Assam's rural areas - EastMojo', 16 May. Available at: https://www.eastmojo.com/top-news/2021/05/16/the-myth-and-reality-of-electricity-connection-in-assams-rural-areas/ (Accessed: 31 January 2022).

Beath, H. *et al.* (2021) 'The cost and emissions advantages of incorporating anchor loads into solar mini-grids in India', *Renewable and Sustainable Energy Transition*, 1, p. 100003. doi: https://doi.org/10.1016/j.rset.2021.100003.

Bhandari, S. *et al.* (2020) 'Performance of WO3-Incorporated Carbon Electrodes for Ambient Mesoscopic Perovskite Solar Cells', *ACS Omega*, 5(1), pp. 422–429. doi: 10.1021/acsomega.9b02934.

Bhatia, M. and Angelou, N. (2015) *Beyond Connections: Energy Access Redefined*. Washington DC. Available at: http://hdl.handle.net/10986/24368.

Bhattacharyya, S. C. *et al.* (2019) 'Solar PV mini-grids versus large-scale embedded PV generation: A case study of Uttar Pradesh (India)', *Energy Policy*. Elsevier, 128, pp. 36–44. doi: 10.1016/J.ENPOL.2018.12.040.

Bisaga, I. and Parikh, P. (2018) 'To climb or not to climb? Investigating energy use behaviour among Solar Home System adopters through energy ladder and social practice lens', *Energy Research & Social Science*. Elsevier, 44, pp. 293–303. doi: 10.1016/J.ERSS.2018.05.019.

Blanchard, R. E. (2015) 'Biomass Heating', in Staffell, I. *et al.* (eds) *Domestic Microgeneration Renewable and Distributed Energy Technologies, Policies and Economics*. Routledge, pp. 77–101. Available at: https://www.routledge.com/Domestic-Microgeneration-Renewable-and-Distributed-Energy-Technologies/Staffell-Brett-Brandon-Hawkes/p/book/9780415810418.

Blodgett, C. *et al.* (2017) 'Accuracy of energy-use surveys in predicting rural mini-grid user consumption', *Energy for Sustainable Development*. Elsevier, 41, pp. 88–105. doi: 10.1016/J.ESD.2017.08.002.
BOS AG (2017) Renewable energy solution for Sarvantara Village - BOS AG. Available at: https://www.bos-ag.com/energy-for-sarvantara-village/ (Accessed: 1 February 2022).

Bos, K., Chaplin, D. and Mamun, A. (2018) 'Benefits and challenges of expanding grid electricity in Africa: A review of rigorous evidence on household impacts in developing countries', *Energy for Sustainable Development*, 44, pp. 64–77. doi: https://doi.org/10.1016/j.esd.2018.02.007.

Business Standard (2021) *Solar power tariffs may rise next fiscal on increased taxes, says report | Business Standard News*. Available at: https://www.business-standard.com/article/economy-policy/solar-power-tariffs-may-rise-next-fiscal-on-increased-taxes-says-report-121102501062_1.html (Accessed: 31 January 2022).

Business Wire (2020) *The Microgrid Opportunity in India, 2024-2025: Identifying Unelectrified Locations that are Best Fit for Electrification Through Microgrids*. Available at: https://www.businesswire.com/news/home/20200414005914/en/The-Microgrid-Opportunity-in-India-2024-2025-Identifying-Unelectrified-Locations-that-are-Best- (Accessed: 31 January 2022).

Cader, C., Blechinger, P. and Bertheau, P. (2016) 'Electrification Planning with Focus on Hybrid Mini-grids – A Comprehensive Modelling Approach for the Global South', *Energy Procedia*. Elsevier, 99, pp. 269–276. doi: 10.1016/J.EGYPRO.2016.10.116.

Candelise, C., Saccone, D. and Vallino, E. (2021) 'An empirical assessment of the effects of electricity access on food security', *World Development*. Pergamon, 141, p. 105390. doi: 10.1016/J.WORLDDEV.2021.105390.

Candelise, C., Winskel, M. and Gross, R. J. K. (2013) 'The dynamics of solar PV costs and prices as a challenge for technology forecasting', *Renewable and Sustainable Energy Reviews*. Pergamon, 26, pp. 96–107. doi: 10.1016/J.RSER.2013.05.012.

Carpaneto, E. and Chicco, G. (2008) 'Probabilistic characterisation of the aggregated residential load patterns', *IET Generation, Transmission & Distribution*. Institution of Engineering and Technology, 2(3), pp. 373-382(9). Available at: https://digital-library.theiet.org/content/journals/10.1049/iet-gtd_20070280.

CEEW (2018) *Addressing Renewable Energy Curtailment: A composite approach*. New Delhi, India. Available at: https://www.ceew.in/sites/default/files/CEEW-Curtailment-Factsheet-26Jun18.pdf.

CEEW Working Group on Mitigation Instruments (2019) *Mitigation Instruments for Achieving India's Climate and Development Goals*. New Delhi, India. Available at: https://www.ceew.in/sites/default/files/CEEW-EDF-Mitigation-Instruments-for-India's-Climate-and-Development-Goals-PDF-14Oct19.pdf.

Centre for Science and Environment (2020) *Renewable Energy Factsheet 7: Mini-Grids*. Available at: https://cdn.cseindia.org/userfiles/07Factsheet-Mini-Grid.pdf (Accessed: 15 February 2022).

Chambon, C. L. *et al.* (2020) 'Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India', *Renewable Energy*. Pergamon, 154, pp. 432–444. doi: 10.1016/J.RENENE.2020.03.002.

Climate Action Tracker (2021) *Climate Action Tracker. India Target update - 01/11/2021*. Available at: https://climateactiontracker.org/climate-target-update-tracker/india/2021-11-01-2/ (Accessed: 31 January 2022).

Comello, S. D. *et al.* (2017) 'Enabling Mini-Grid Development in Rural India', *World Development*, 93(Supplement C), pp. 94–107. doi: https://doi.org/10.1016/j.worlddev.2016.12.029.

Cozzi, L., Tonolo, G. and Wetzel, D. (2021) *The pandemic continues to slow progress towards universal energy access, IEA Commentary*. Available at: https://www.iea.org/commentaries/the-pandemic-continues-to-slow-progress-towards-universal-energy-access.

Deshmukh, R. *et al.* (2019) 'Geospatial and techno-economic analysis of wind and solar resources in India', *Renewable Energy*. Pergamon, 134, pp. 947–960. doi: 10.1016/J.RENENE.2018.11.073.

Dhundhara, S., Verma, Y. P. and Williams, A. (2018) 'Techno-economic analysis of the lithium-ion and lead-acid battery in microgrid systems', *Energy Conversion and Management*. Pergamon, 177, pp. 122–142. doi: 10.1016/J.ENCONMAN.2018.09.030.

Dominguez, C., Orehounig, K. and Carmeliet, J. (2021) 'Understanding the path towards a clean energy transition and post-electrification patterns of rural households', *Energy for Sustainable Development*. Elsevier, 61, pp. 46–64. doi: 10.1016/J.ESD.2021.01.002.

ecoinvent (2022) *ecoinvent.* Available at: https://ecoinvent.org/ (Accessed: 31 January 2022).

Element Energy and De Montfort University (2012) *Demand side response in the non-domestic sector Final report for Ofgem Demand side response in the non-domestic sector Final report*. Available at: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/07/Demand-Side-Response-in-the-non-domestic-sector.pdf (Accessed: 1 February 2022).

Ershad, A. M. *et al.* (2020) 'Managing Power Demand from Air Conditioning Benefits Solar PV in India Scenarios for 2040', *Energies*, 13(9). doi: 10.3390/en13092223.

ESMAP (2000) Mini-Grid Design Manual. Available at: https://www.esmap.org/sites/default/files/esmap-files/TR_minigriddesignmanual21364.pdf (Accessed: 18 February 2022).

ESMAP (2019) *Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers*. Washington DC. Available at: https://openknowledge.worldbank.org/handle/10986/31926.

European Commission (2019) *JRC Photovoltaic Geographical Information System (PVGIS) – European Commission*. Available at: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP (Accessed: 31 January 2022).

Evans, S. M. and Birchenough, A. C. (2001) 'Community-based management of the environment: lessons from the past and options for the future', *Aquatic Conservation: Marine and Freshwater Ecosystems*, 11(2), pp. 137–147. doi: https://doi.org/10.1002/aqc.434.

Feron, S. (2016) 'Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review', *Sustainability*, 8(12), p. 1326. Available at: https://www.mdpi.com/2071-1050/8/12/1326.

Few, S. *et al.* (2016) 'Energy Storage for Balancing Intermittent Renewables: Outlook for a Range of Technologies up to 2030'. Imperial College London.

Few, S., Schmidt, O., Offer, G. J., *et al.* (2018) 'Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: An analysis informed by expert elicitations', *Energy Policy*. Elsevier, 114, pp. 578–590. doi: 10.1016/J.ENPOL.2017.12.033.

Few, S. *et al.* (2022) 'Electricity demand in populations gaining access: Impact of rurality and climatic conditions, and implications for microgrid design', *Energy for Sustainable Development*. Elsevier, 66, pp. 151–164. doi: 10.1016/J.ESD.2021.11.008.

Few, S., Schmidt, O. and Gambhir, A. (2019) 'Energy access through electricity storage: Insights from technology providers and market enablers', *Energy for Sustainable Development*. Elsevier, 48, pp. 1–10. doi: 10.1016/J.ESD.2018.09.008.

Fosli, J. K., Reddy, A. A. and Rani, R. (2021) 'The Policy of Free Electricity to Agriculture Sector: Implications and Perspectives of the Stakeholders in India', *Journal of Development Policy and Practice*, 6(2), pp. 252–269. doi: 10.1177/24551333211025203.

Fthenakis, V. et al. (2020) 'Sustainability evaluation of CdTe PV: An update', *Renewable and Sustainable Energy Reviews*, 123, p. 109776. doi: https://doi.org/10.1016/j.rser.2020.109776.

Fu, R., James, T. L. and Woodhouse, M. (2015) 'Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness', *IEEE Journal of Photovoltaics*, 5(2), pp. 515–524. doi: 10.1109/JPHOTOV.2014.2388076.

Ganguly, R. *et al.* (2020) 'Mini grids and enterprise development: A study of aspirational change and business outcomes among rural enterprise owners in India', *Energy for Sustainable Development*. Elsevier, 56, pp. 119–127. doi: 10.1016/J.ESD.2020.04.004.

Gaur, K. *et al.* (2016) 'Analysing the electricity demand pattern', in *2016 National Power Systems Conference (NPSC)*, pp. 1–6. doi: 10.1109/NPSC.2016.7858969.

Gerbec, D., Gasperic, S. and Gubina, F. (2003) 'Determination and allocation of typical load profiles to the eligible consumers', in *2003 IEEE Bologna Power Tech Conference Proceedings*, pp. 5 pp. Vol.1-. doi: 10.1109/PTC.2003.1304159.

Ghosh, A. (2020a) 'Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive review', *Journal of Cleaner Production*. Elsevier, 276, p. 123343. doi: 10.1016/J.JCLEPRO.2020.123343.

Ghosh, A. (2020b) 'Soiling Losses: A Barrier for India's Energy Security Dependency from Photovoltaic Power', *Challenges*, 11(1). doi: 10.3390/challe11010009.

Gils, H. C. (2014) 'Assessment of the theoretical demand response potential in Europe', *Energy*. Pergamon, 67, pp. 1–18. doi: 10.1016/J.ENERGY.2014.02.019.

Global Off-Grid Lighting Association (2021) *Global Off-Grid Solar Market Report Semi-Annual Sales and Impact Data: January – June 2021*.

GMI Research (2020) *India Mini Grid Market Opportunities & Forecast 2020-2027*. Available at: https://www.gmiresearch.com/report/india-mini-grid-market/ (Accessed: 31 January 2022).

Graber, S. *et al.* (2019) 'Perceptions towards solar mini-grid systems in India : A multi- stakeholder analysis', *Natural Resources Forum*, 43(4), pp. 253–266. doi: 10.1111/1477-8947.12181.

Green, M. *et al.* (2021) 'Solar cell efficiency tables (version 57)', *Progress in Photovoltaics: Research and Applications*, 29(1), pp. 3–15. doi: https://doi.org/10.1002/pip.3371.

Gupta, U. (2021) *Transforming lives with solar mini-grids*. Available at: https://www.pv-magazine.com/2021/07/12/transforming-lives-through-solar-mini-grids/ (Accessed: 31 January 2022).

Gür, T. M. (2018) 'Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage', *Energy and Environmental Science*. Royal Society of Chemistry, pp. 2696–2767. doi: 10.1039/c8ee01419a.

Hartvigsson, E. *et al.* (2021) 'Linking household and productive use of electricity with mini-grid dimensioning and operation', *Energy for Sustainable Development*. Elsevier, 60, pp. 82–89. doi: 10.1016/J.ESD.2020.12.004.

Hartvigsson, E. and Ahlgren, E. O. (2018) 'Comparison of load profiles in a mini-grid: Assessment of performance metrics using measured and interview-based data', *Energy for Sustainable Development*. Elsevier, 43, pp. 186–195. doi: 10.1016/J.ESD.2018.01.009.

Hazelton, J., Bruce, A. and MacGill, I. (2014) 'A review of the potential benefits and risks of photovoltaic hybrid mini-grid systems', *Renewable Energy*. Pergamon, 67, pp. 222–229. doi: 10.1016/J.RENENE.2013.11.026.

Hesse, H. *et al*. (2017) 'Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids', *Energies*. MDPI AG, 10(12), p. 2107. doi: 10.3390/en10122107.

Holstenkamp, L. (2019) 'What do we know about cooperative sustainable electrification in the global South? A synthesis of the literature and refined social-ecological systems framework', *Renewable and Sustainable Energy Reviews*, 109, pp. 307–320. doi: https://doi.org/10.1016/j.rser.2019.04.047.

HOMER Energy LLC (2022) HOMER - *Hybrid Renewable and Distributed Generation System Design Software*. Available at: https://www.homerenergy.com/ (Accessed: 31 January 2022).

IEA (2017) *Energy Access Outlook*.

IEA (2020a) *India 2020: Energy Policy Review*. Available at: https://iea.blob.core.windows.net/assets/2571ae38-c895-430e-8b62-bc19019c6807/India_2020_Energy_Policy_Review.pdf.

IEA (2020b) *World Energy Outlook 2020*. Available at: https://www.iea.org/reports/world-energy-outlook-2020.

IEA (2021a) *Global population without access to electricity by region*, 2000-2021. Available at: ttps://www.iea.org/data-and-statistics/charts/global-population-without-access-to-electricity-by-region-2000-2021-2.
IEA (2021b) *Perform, Achieve, Trade (PAT) Scheme – Policies - IEA*. Available at: https://www.iea.org/policies/1780-perform-achieve-trade-pat-scheme (Accessed: 31 January 2022).

IEA (2021c) *SDG7 Data and Projections: Access to electricity*. Available at: www.iea.org/reports/sdg7-data-and-projections/access-to-electricity.

IEA (2021d) *Uttar Pradesh Mini-Grid Policy 2016 – Policies - IEA*. Available at: https://www.iea.org/policies/6374-uttar-pradesh-mini-grid-policy-2016 (Accessed: 31 January 2022).

Indian Ministry of Power (2021) *Pradhan Mantri Sahaj Bijli Har Ghar Yojana - Saubhagya*. India. Available at: https://powermin.gov.in/en/content/saubhagya.

Institute for Energy Economics & Financial Analysis (2018) *New National Electricity Plan Reinforces Intent Toward 275 Gigawatts of Renewables-Generated Electricity by 2027*. Available at: https://ieefa.org/ieefa-india-new-national-electricity-plan-reinforces-intent-toward-275-gigawatts-of-renewables-generated-electricity-by-2027/ (Accessed: 4 February 2022).

IRENA (2016) *Innovation Outlook: Renewable Mini-Grids*. Abu Dhabi.

IRENA (2018) *Off-Grid Renewable Energy Solutions: Global and regional status and trends*. Available at: https://www.irena.org/publications/2018/Jul/Off-grid-Renewable-Energy-Solutions.

IRENA (2021) *Renewable Power Generation Costs in 2020*. Available at: https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020.

Jaffer, H. (2016) *Mini-grids in India: Current Challenges and Future Strategies*. Available at: https://www.selcofoundation.org/wp-content/uploads/2017/04/IAP_Mini-gridsIndiaReportTATA_Huda.pdf.

Jayachandran, M. and Ravi, G. (2017) 'Design and Optimization of Hybrid Micro-Grid System', *Energy Procedia*. Elsevier, 117, pp. 95–103. doi: 10.1016/J.EGYPRO.2017.05.111.

Kang, C. *et al*. (2018) 'Big Data Analytics in China's Electric Power Industry: Modern Information, Communication Technologies, and Millions of Smart Meters', *IEEE Power and Energy Magazine*, 16(3), pp. 54–65. doi: 10.1109/MPE.2018.2790819.

Katre, A., Tozzi, A. and Bhattacharyya, S. (2019) 'Sustainability of community-owned mini-grids: evidence from India', *Energy, Sustainability and Society*, 9(1), p. 2. doi: 10.1186/s13705-018-0185-9.

Kear, G., Shah, A. A. and Walsh, F. C. (2012) 'Development of the all vanadium redox flow battery for energy storage : a review of technological, financial and policy aspects', *International Journal of Energy Research*, (36), pp. 1105–1120. doi: 10.1002/er.1863.

Kittner, N., Gheewala, S. H. and Kammen, D. M. (2016) 'Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid', *Renewable Energy*. Pergamon, 99, pp. 410–419. doi: 10.1016/J.RENENE.2016.07.023.

Leung, P. *et al*. (2017) 'Recent developments in organic redox flow batteries: A critical review', *Journal of Power Sources*. Elsevier B.V., pp. 243–283. doi: 10.1016/j.jpowsour.2017.05.057.

Lhendup, T. (2008) 'Rural electrification in Bhutan and a methodology for evaluation of distributed generation system as an alternative option for rural electrification', *Energy for Sustainable Development*. Elsevier, 12(3), pp. 13–24. doi: 10.1016/S0973-0826(08)60434-2.

Louie, H. and Dauenhauer, P. (2016) 'Effects of load estimation error on small-scale off-grid photovoltaic system design, cost and reliability', *Energy for Sustainable Development*. Elsevier, 34, pp. 30–43. doi: 10.1016/J.ESD.2016.08.002.

Ludin, N. A. *et al.* (2018) 'Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review', *Renewable and Sustainable Energy Reviews*. Pergamon, 96, pp. 11–28. doi: 10.1016/J.RSER.2018.07.048.

Maani, T. et al. (2020) 'Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels', *Science of The Total Environment*, 735, p. 138827. doi: https://doi.org/10.1016/j.scitotenv.2020.138827.

Mahapatra, S. and Dasappa, S. (2012) 'Rural electrification: Optimising the choice between decentralised renewable energy sources and grid extension', *Energy for Sustainable Development*. Elsevier, 16(2), pp. 146–154. doi: 10.1016/J.ESD.2012.01.006.

Mahtta, R., Joshi, P. K. and Jindal, A. K. (2014) 'Solar power potential mapping in India using remote sensing inputs and environmental parameters', *Renewable Energy*. Pergamon, 71, pp. 255–262. doi: 10.1016/J.RENENE.2014.05.037.

Mandelli, S. *et al.* (2016) 'Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review', *Renewable and Sustainable Energy Reviews*. Pergamon, 58, pp. 1621–1646. doi: 10.1016/J.RSER.2015.12.338.

Marks, S. J. and Davis, J. (2012) 'Does User Participation Lead to Sense of Ownership for Rural Water Systems? Evidence from Kenya', World Development, 40(8), pp. 1569–1576. doi: https://doi.org/10.1016/j.worlddev.2012.03.011.

McCall, M. and Santana, S. (2018) *Closing the Circuit: Stimulating End-Use Demand for Rural Electrification.*

McKenna, E., Doylend, N. and Thomson, M. (2013) 'Case-study of end-use energy demand in a commercial office building : implications for the development of high-resolution energy demand models', in *Fifth German-Austrian IBPSA Conference*. Available at: http://www.ibpsa.org/proceedings/bausimPapers/2014/p1114_final.pdf.

McKenna, E., Thomson, M. and Barton, J. (2015) 'CREST Demand Model'. Loughborough University. doi: 10.17028/rd.lboro.2001129.v8.

Ministry of Housing and Urban Affairs (2022) *Level of Urbanisation: Ministry of Housing and Urban Affairs, Goverment of India*. Available at: https://mohua.gov.in/cms/level-of-urbanisation.php (Accessed: 31 January 2022).

Ministry of Petroleum and Natural Gas (2021) *Pradhan Mantri Ujjwala Yojana 2.0*. India. Available at: www.pmuy.gov.in.

Mohapatra, D., Jaeger, J. and Wiemann, M. (2019) *Private Sector Driven Business Models for Clean Energy Mini-Grids: Lessons learnt from South and South-East-Asia*. Brussels. Available at: https://www.ruralelec.org/publications/private-sector-driven-business-models-clean-energy-mini-grids-lessons-learnt-south-and (Accessed: 15 February 2022).

Morales González, R. *et al.* (2018) 'Demand Response of Medical Freezers in a Business Park Microgrid', in *Proceedings of the 7th International Conference on Smart Cities and Green ICT Systems*. Setubal, PRT: SCITEPRESS - Science and Technology Publications, Lda (SMARTGREENS 2018), pp. 120–129. doi: 10.5220/0006801001200129.

Muratori, M. and Rizzoni, G. (2016) 'Residential Demand Response: Dynamic Energy Management and Time-Varying Electricity Pricing', *IEEE Transactions on Power Systems*, 31(2), pp. 1108–1117. doi: 10.1109/TPWRS.2015.2414880.

Namaganda-Kiyimba, J. and Mutale, J. (2020) 'Gender Considerations in Load Estimation for Rural Electrification', in *2020 IEEE Conference on Technologies for Sustainability* (SusTech), pp. 1–8. doi: 10.1109/SusTech47890.2020.9150501.

Narayan, N. *et al.* (2019) 'Quantifying the Benefits of a Solar Home System-Based DC Microgrid for Rural Electrification', *Energies*. Multidisciplinary Digital Publishing Institute, 12(5), p. 938. doi: 10.3390/en12050938.

Narula, K., Nagai, Y. and Pachauri, S. (2012) 'The role of Decentralized Distributed Generation in achieving universal rural electrification in South Asia by 2030', *Energy Policy*. Elsevier, 47, pp. 345–357. doi: 10.1016/J.ENPOL.2012.04.075.

Nouni, M. R., Mullick, S. C. and Kandpal, T. C. (2008) 'Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply', *Renewable and Sustainable Energy Reviews*. Pergamon, 12(5), pp. 1187–1220. doi: 10.1016/J.RSER.2007.01.008.

Nykvist, B. and Nilsson, M. (2015) 'Rapidly falling costs of battery packs for electric vehicles', *Nature Climate Change*, 5(4), pp. 329–332. doi: 10.1038/nclimate2564.

Okapi Research and Advisory (2017) *Beyond Off-grid: Integrating Mini-grids with India's Evolving Electricity System*. Available at: www.rockefellerfoundation.org/wp-content/uploads/Integrating-Mini-Grids-with-Indias-Evolving-Electricity-System-May-2017.pdf.

Olivetti, E. A. *et al.* (2017) 'Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals', *Joule*. Cell Press, 1(2), pp. 229–243. doi: 10.1016/J.JOULE.2017.08.019.

Ortega-Arriaga, P. *et al.* (2021) 'Grid versus off-grid electricity access options: A review on the economic and environmental impacts', *Renewable and Sustainable Energy Reviews*, 143, p. 110864. doi: https://doi.org/10.1016/j.rser.2021.110864

Palit, D. et al. (2013) 'The trials and tribulations of the Village Energy Security Programme (VESP) in India', *Energy Policy*, 57, pp. 407–417. doi: https://doi.org/10.1016/j.enpol.2013.02.006..

Palit, D. and Sarangi, G. K. (2014) 'Renewable energy based mini-grids for enhancing electricity access: Experiences and lessons from India', in *2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE)*, pp. 1–8.

Pankadan, S., Nikam, S. and Anwer, N. (2021) 'An Analysis for Management of End-of-Life Solar PV in India', in Bose, M. and Modi, A. (eds) *Proceedings of the 7th International Conference on Advances in Energy Research*. Singapore: Springer Singapore, pp. 1361–1371.

De Paola, A., Angeli, D. and Strbac, G. (2017) 'Convergence and optimality of a new iterative price-based scheme for distributed coordination of flexible loads in the electricity market', in *2017 IEEE 56th Annual Conference on Decision and Control (CDC)*, pp. 1386–1393. doi: 10.1109/CDC.2017.8263848.

Pfenninger, S. and Staffell, I. (2016) 'Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data', *Energy*. Pergamon, 114, pp. 1251–1265. doi: 10.1016/J.ENERGY.2016.08.060.

Pfenninger, S. and Staffell, I. (2022) *Renewables.ninja*. Available at: https://www.renewables.ninja/ (Accessed: 31 January 2022).

Poblete-Cazenave, M. and Pachauri, S. (2021) 'A model of energy poverty and access: Estimating household electricity demand and appliance ownership', *Energy Economics*, 98, p. 105266. doi: https://doi.org/10.1016/j.eneco.2021.105266.

Polverini, D., Dodd, N. and Espinosa, N. (2021) 'Potential regulatory approaches on the environmental impacts of photovoltaics: Expected improvements and impacts on technological innovation', *Progress in Photovoltaics: Research and Applications*, 29(1), pp. 83–97. doi: https://doi.org/10.1002/pip.3344.

Ponoćko, J. and Milanović, J. V (2018) 'Forecasting Demand Flexibility of Aggregated Residential Load Using Smart Meter Data', *IEEE Transactions on Power Systems*, 33(5), pp. 5446–5455. doi: 10.1109/TPWRS.2018.2799903.

Posada, J. O. G. *et al.* (2017) 'Aqueous batteries as grid scale energy storage solutions', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 1174–1182. doi: 10.1016/j.rser.2016.02.024.

Power for All (2018) *Fact Sheet: Mini-Grids in India: Mini-Grid Finance and Business Models*. Available at: https://www.powerforall.org/resources/fact-sheets/fact-sheet-india-mini-grids.

Power for All (2019) *Powering Jobs Census 2019: The Energy Access Workforce, Power for All Report*. Available at: https://www.powerforall.org/resources/reports/powering-jobs-census-2019-energy-access-workforce#:~:text=Download%20the%20Powering%20Jobs%20Census,electricity%20for%20the%20first%20time. [Accessed 15th October 2021].

Power for All (2020) 'Power for All Fact Sheet: Mini-grids for productive uses of energy (PUE) in agriculture'. Available at: https://www.powerforall.org/resources/fact-sheets/fact-sheet-mini-grids-and-agriculture.

Rajya Sabha Secretariat (2021) *Indian States Official Sites*. Available at: https://rajyasabha.nic.in/rsnew/official_sites/statelegis.asp (Accessed: 31 January 2022).

Ramírez-Mendiola, J. L., Grünewald, P. and Eyre, N. (2017) 'The diversity of residential electricity demand – A comparative analysis of metered and simulated data', *Energy and Buildings*. Elsevier, 151, pp. 121–131. doi: 10.1016/J.ENBUILD.2017.06.006.

Reber, T. et al. (2018) 'Tariff considerations for micro-grids in Sub-Saharan Africa'. Available at: https://www.nrel.gov/docs/fy18osti/69044.pdf (Accessed: 18 February 2022).

Reniers, J. M., Mulder, G. and Howey, D. A. (2020) 'Unlocking extra value from grid batteries using advanced models', *arXiv*. arXiv, p. 229355. doi: 10.1016/j.jpowsour.2020.229355.

Richmond, J. and Urpelainen, J. (2019) 'Electrification and appliance ownership over time: Evidence from rural India', *Energy Policy*. Elsevier, 133, p. 110862. doi: 10.1016/J.ENPOL.2019.06.070.

Riva, F. *et al.* (2018) 'Electricity access and rural development: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling', *Energy for Sustainable Development*, 43, pp. 203–223. doi: https://doi.org/10.1016/j.esd.2018.02.003.

Riva, F. *et al.* (2019) 'Soft-linking energy demand and optimisation models for local long-term electricity planning: An application to rural India', *Energy*. Pergamon, 166, pp. 32–46. doi: 10.1016/J.ENERGY.2018.10.067.

Rogers, J. (2008) *Residential Consumption of Electricity in India Documentation of Data and Methodology. Background Paper India: Strategies for Low Carbon Growth*. Available at: http://moef.gov.in/wp-content/uploads/2018/04/Residentialpowerconsumption.pdf (Accessed: 1 February 2022).

Sajjad, I. A., Chicco, G. and Napoli, R. (2016) 'Definitions of Demand Flexibility for Aggregate Residential Loads', *IEEE Transactions on Smart Grid*, 7(6), pp. 2633–2643. doi: 10.1109/TSG.2016.2522961.

Sandwell, P., Chambon, C., *et al.* (2016) ‘Analysis of energy access and impact of modern energy sources in unelectrified villages in Uttar Pradesh’, *Energy for Sustainable Development*. Elsevier, 35, pp. 67–79. doi: 10.1016/J.ESD.2016.09.002.

Sandwell, P., Chan, N. L. A., *et al.* (2016) ‘Off-grid solar photovoltaic systems for rural electrification and emissions mitigation in India’, *Solar Energy Materials and Solar Cells*, 156, pp. 147–156. doi: http://dx.doi.org/10.1016/j.solmat.2016.04.030.

Sandwell, P. (2022) *GitHub - phil-sandwell/CLOVER: CLOVER mini-grid simulation and optimisation for supporting rural electrification in developing countries*. Available at: https://github.com/phil-sandwell/CLOVER (Accessed: 31 January 2022).

Sandwell, P., Ekins-Daukes, N. and Nelson, J. (2017) ‘What are the greatest opportunities for PV to contribute to rural development?’, *Energy Procedia*. Elsevier, 130, pp. 139–146. doi: 10.1016/J.EGYPRO.2017.09.416.

Sandwell, P., Wheeler, S. and Nelson, J. (2017) *Supporting rural electrification in developing countries*.

Scherfler, M. (2020) *Tamil Nadu Draft Solar Energy Action Plan 2023 (SEAP)*.

Schiffer, J. *et al.* (2007) ‘Model prediction for ranking lead-acid batteries according to expected lifetime in renewable energy systems and autonomous power-supply systems’, *Journal of Power Sources*. Elsevier, 168(1), pp. 66–78. doi: 10.1016/J.JPOWSOUR.2006.11.092.

Schmidt, O. *et al.* (2017) ‘The future cost of electrical energy storage based on experience rates’, *Nature Energy*. Nature Publishing Group SN -, 2, pp. 17110 EP-. Available at: http://dx.doi.org/10.1038/nenergy.2017.110.

Schmidt, O. *et al.* (2018) ‘Projecting the future levelized cost of electricity storage technologies’, *Joule*. Elsevier Inc., [submitted, pp. 1–20. doi: 10.1016/J.JOULE.2018.12.008.

Sen, R. and Bhattacharyya, S. C. (2014) ‘Renewable Energy-Based Mini-Grid for Rural Electrification: Case Study of an Indian Village’, in *Green Energy and Technology*. Springer, Cham, pp. 203–232. doi: 10.1007/978-3-319-04816-1_9.

Shah, T., Giordano, M. and Mukherji, A. (2012) ‘Political economy of the energy-groundwater nexus in India: exploring issues and assessing policy options’, *Hydrogeology Journal*, 20(5), pp. 995–1006. doi: 10.1007/s10040-011-0816-0.

Short, J. A., Infield, D. G. and Freris, L. L. (2007) ‘Stabilization of Grid Frequency Through Dynamic Demand Control’, *IEEE Transactions on Power Systems*, 22(3), pp. 1284–1293. doi: 10.1109/TPWRS.2007.901489.
Shyu, C. W. (2013) ‘End-users’ experiences with electricity supply from stand-alone mini-grid solar PV power stations in rural areas of western China’, *Energy for Sustainable Development*. Elsevier, 17(4), pp. 391–400. doi: 10.1016/J.ESD.2013.02.006.

Singh, R. K. (2019) *Tata Power, Rockefeller Foundation plan 10,000 microgrids across rural India*. Available at: https://www.livemint.com/industry/energy/tata-power-rockefeller-foundation-plan-10-000-microgrids-across-rural-india-11572869947712.html (Accessed: 31 January 2022).

Skyllas-Kazacos, M. *et al.* (2011) ‘Progress in Flow Battery Research and Development’, *Journal of The Electrochemical Society*. The Electrochemical Society, 158(8), p. R55. doi: 10.1149/1.3599565.

Sowe, J. *et al.* (2020) ‘How Can Insights from Degradation Modelling Inform Operational Strategies to Increase the Lifetime of Li-Ion Batteries in Islanded Mini-Grids?’, *ECS Meeting Abstracts*, MA2020-02(45), pp. 3780–3780. doi: 10.1149/MA2020-02453780mtgabs.

Staffell, I. and Pfenninger, S. (2016) ‘Using bias-corrected reanalysis to simulate current and future wind power output’, *Energy*. Pergamon, 114, pp. 1224–1239. doi: 10.1016/J.ENERGY.2016.08.068.

Stevanato, N. *et al.* (2020) ‘Long-term sizing of rural microgrids: Accounting for load evolution through multi-step investment plan and stochastic optimization’, *Energy for Sustainable Development*. Elsevier, 58, pp. 16–29. doi: 10.1016/J.ESD.2020.07.002.

Subramony, V. A., Doolla, S. and Chandorkar, M. (2017) ‘Microgrids in India’, *IEEE Electrification Magazine*, June 2017.

Sun, X. *et al.* (2019) ‘Supply risks of lithium-ion battery materials: An entire supply chain estimation’, *Materials Today Energy*. Elsevier, 14, p. 100347. doi: 10.1016/J.MTENER.2019.100347.

Suryad, V. A., Doolla, S. and Chandorkar, M. (2017) ‘Microgrids in India: Possibilities and Challenges’, *IEEE Electrification Magazine*, 5(2), pp. 47–55. doi: 10.1109/MELE.2017.2685880.

Sustainable Energy for All (2019a) *Integrated Electrification Pathways for Universal Access to Electricity: A Primer*.

Sustainable Energy for All (2019b) *Lasting impact: Sustainable off-grid solar delivery models to power health and education*. Available at: www.seforall.org/publications/lasting-impact-sustainable-off-grid-solar-delivery-models.

Sustainable Energy for All and Bloomberg NEF (2020a) *State of the Global Mini-grids Market Report 2020. Case Study - India (Bihar)*. Available at: https://mini-grids.org/market-report-2020/.

Sustainable Energy for All and Bloomberg NEF (2020b) *State of the Global Mini-grids Market Report 2020*. Available at: https://mini-grids.org/market-report-2020.

Sustainable Energy for All and The Rockfeller Foundation (2020) *The Electrifying Economies Project*.

Technical University of Denmark (2022) *Global Wind Atlas*. Available at: https://globalwindatlas.info/ (Accessed: 1 February 2022).

Tenenbaum, B. *et al.* (2014) *From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa*. Washington DC.

Tenenbaum, B., Greacen, C. and Vaghela, D. (2018) *Mini-Grids and Arrival of the Main Grid : Lessons from Cambodia, Sri Lanka, and Indonesia*. Washington DC. Available at: http://hdl.handle.net/10986/29018.

The Rockfeller Foundation (2020) *Powering an Inclusive Covid-19 Recovery*. Available at: https://www.rockefellerfoundation.org/report/powering-an-inclusive-covid-19-recovery/.

The World Bank (2021) *Access to electricity (% of population) - India | Data*. Available at: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=IN (Accessed: 31 January 2022).

Thiruvananthapuram, T. N. (2018) *Micro hydro power gains traction in State - The Hindu*. Available at: https://www.thehindu.com/news/national/kerala/micro-hydro-power-gains-traction-in-state/article22860559.ece (Accessed: 1 February 2022).

Tiewsoh, L. S., Jirásek, J. and Sivek, M. (2019) 'Electricity Generation in India: Present State, Future Outlook and Policy Implications', *Energies*, 12(7). doi: 10.3390/en12071361.

Tsang, M. P., Sonnemann, G. W. and Bassani, D. M. (2016) 'Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies', *Solar Energy Materials and Solar Cells*. North-Holland, 156, pp. 37–48. doi: 10.1016/J.SOLMAT.2016.04.024.

UKICERI (2020) *Electricity Access and Climate Change Mitigation in India: The Role of Microgrids*.

Ulsrud, K. et al. (2011) 'The Solar Transitions research on solar mini-grids in India: Learning from local cases of innovative socio-technical systems', *Energy for Sustainable Development*, 15(3), pp. 293–303. doi: https://doi.org/10.1016/j.esd.2011.06.004.

United Nations Statistical Division (2021) *The Sustainable Development Goals Report 2021*. Available at: https://unstats.un.org/sdgs/report/2021/.

Vaalma, C. *et al.* (2018) 'A cost and resource analysis of sodium-ion batteries', *Nature Reviews Materials*. Nature Publishing Group, pp. 1–11. doi: 10.1038/natrevmats.2018.13.

Wai, C. H. *et al.* (2015) 'Cooling Devices in Demand Response: A Comparison of Control Methods', *IEEE Transactions on Smart Grid*, 6(1), pp. 249–260. doi: 10.1109/TSG.2014.2358579.

WEO (2018) *World Energy Outlook: Access to electricity database*. Available at: https://www.iea.org/sdg/electricity/.

van der Werff, E., Thogersen, J. and de Bruin, W. (2018) 'Changing Household Energy Usage: The Downsides of Incentives and How to Overcome Them', *IEEE Power and Energy Magazine*, 16(1), pp. 42–48. doi: 10.1109/MPE.2017.2759884.

Whitacre, J. F. *et al.* (2012) 'An aqueous electrolyte, sodium ion functional, large format energy storage device for stationary applications', *Journal of Power Sources*. Elsevier, 213, pp. 255–264. doi: 10.1016/j.jpowsour.2012.04.018.

Williams, N. J. *et al.* (2017) 'Load characteristics of East African microgrids', in 2017 *IEEE PES PowerAfrica*, pp. 236–241. doi: 10.1109/PowerAfrica.2017.7991230.

Wilson, G. M. *et al.* (2020) 'The 2020 photovoltaic technologies roadmap', *Journal of Physics D: Applied Physics*, 53(49), p. 493001. doi: 10.1088/1361-6463/ab9c6a.

Wu, B. *et al.* (2020) 'Battery digital twins: Perspectives on the fusion of models, data and artificial intelligence for smart battery management systems', *Energy and AI*. Elsevier, 1, p. 100016. doi: 10.1016/j.egyai.2020.100016.

Zhang, M. *et al.* (2012) 'Capital Cost Sensitivity Analysis of an All-Vanadium Redox-Flow Battery', *Journal of The Electrochemical Society*. The Electrochemical Society, 159(8), pp. A1183–A1188. doi: 10.1149/2.041208jes.

Zhong, H. *et al.* (2015) 'An Efficient Decomposition Method for the Integrated Dispatch of Generation and Load', *IEEE Transactions on Power Systems*, 30(6), pp. 2923–2933. doi: 10.1109/TPWRS.2014.2381672.

Zhong, H., Xie, L. and Xia, Q. (2013) 'Coupon Incentive-Based Demand Response: Theory and Case Study', *IEEE Transactions on Power Systems*, 28(2), pp. 1266–1276. doi: 10.1109/TPWRS.2012.2218665.