vivideconomics ARUP

Opportunities to enhance electricity network efficiency

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The views expressed here are those of the authors, Vivid Economics and Arup, and do not necessarily represent those of the Department for International Development.

Executive summary

This project seeks to investigate whether and how the application of emerging technologies and techniques can promote electricity network efficiencies and thereby achieve low carbon development goals. Well-targeted programs that promote electricity network efficiency, potentially funded through the International Climate Fund (ICF), could support the Sustainable Energy For All (SE4All) core objective of providing energy that is accessible, cleaner and more efficient.

The highest impact opportunities in relation to enhancing network efficiency are likely to be in enhancing understanding of emerging applications and leveraging private finance to drive adoption of those applications. To help capture these opportunities, this report seeks to identify and investigate applications that fulfil four criteria:

– The application is not well understood technically and in terms of the policy and economic barriers that may prevent its application, and so further research and understanding would likely be of benefit to the climate and development communities;
– The application is well placed to leverage private finance;
– The application actively promotes, or at least does not obstruct, ‘leapfrogging’ by facilitating adoption of decentralising technologies, such as storage, distributed generation or smart meters, and innovative business models in electricity supply; and
– The application has clear greenhouse gas abatement potential.

Analysis of a range of potential network efficiency investments against these criteria suggests that four particular applications merit further investigation. These are:

– Grid-connected mini-grids, where a user or users are supplied with power from local generation, storage and control systems (a ‘mini-grid’) that are capable of operating either in combination with the grid or on a stand-alone basis;
– Grid extension augmented with smart technologies, where traditional ‘poles and wires’ grid extensions are complemented with distributed storage, generation and control systems;
– ‘Grid ready’ off-grid mini-grids, where stand-alone mini-grids are designed with the technical and commercial requirements of future grid connection in mind; and
– Smart metering and Information Communication Technology (ICT) to address non-technical losses, where remote metering and supporting measures are used to target power theft.

These four applications were investigated through a technical overview, a range of case studies and a high-level cross-country analysis to identify prospective places to implement them. Based on this, the study suggests several areas where further action by donors and policy-makers can promote network efficiency.

There is potential for large-scale uptake of grid-connected mini-grids in future, and an associated opportunity for investments of this type to enhance network efficiency. Two main groups of grid-connected mini-grid case studies are examined. One set uses ‘anchor customers’ to underpin the commercial expansion of electricity access to communities through a grid-connected mini-grid. A second set examines generation, storage and management systems installed by a diverse group of users including petrol stations, hospitals and automated teller machines to mitigate the effects of an unreliable grid and displace diesel generation. Whilst the donor community, including DFID, the International Finance Corporation and the Rockefeller Foundation, have been active in advancing the anchor customer approach, there is an opportunity to devote more attention to unlocking the potential of single-user mini-grids to enhance network efficiency. Given the widespread use of diesel generation by a diverse range of users to provide reliable electricity supply, there is great potential for adoption of advanced decentralised mini-grid type technologies in their stead.

A key area for action by donors and policy-makers is to help develop innovative business models that could capture the network efficiency benefits of mini-grid investments that are, at present, focused solely on supporting reliable supply to an end user. Technically grid-connected mini-grid approaches of this type are capable of supporting network efficiency by drawing power from the wider grid when supply is ample and exporting to the grid when supply is tight. However, where these systems are installed by end users, the focus is typically only on the user's own reliability needs; the complicated matter of providing the wider grid with 'stabilisation services' is unlikely to be considered. More sophisticated approaches by either specialised energy service companies (ESCOs) or utilities could play a crucial role in unlocking these network benefits. The donor community has played an important role in developing innovative business models in relation to the anchor customer model discussed above; potentially it could play a similar role in unlocking the potential of single-user mini-grids to stabilise the network. These business models could potentially serve both businesses and households, though tailored approaches may well be needed.

Grid extension augmented with smart technologies is at an early stage of application even in developing countries and a 'watching brief' for future application in developing contexts appears most appropriate. The two case studies examined are from developed countries and demonstrate two major areas of potential application: use of active network management to support higher levels of local renewable generation; and use of storage to enhance reliability and avoid expenditure on upgrade the local distribution network.

Technical assistance and socialisation of international experience on making mini-grids 'grid-ready' can improve the efficiency of expanding electricity access. Grid-readiness should support mini-grid investment, thereby reducing the cost and increasing the efficiency of expanding access. Both technical and commercial factors can create uncertainty over the fate of mini-grid infrastructure in the event of interconnection with the main grid. Three case studies explored in this report illustrate both the potential for grid-readiness to be poorly handled, leading to redundant energy infrastructure, as well as for it to be managed well through clear connection arrangements and power purchase agreements for small power producers. Some countries have more developed connection arrangements than others, indicating the potential benefit of socialising this experience.

A potential further opportunity for the donor community is to partner with utilities that seek to address non-technical losses; while technical aspects are important, these approaches need a wider strategy focusing on the social and political aspects of the problem. Three case studies illustrate that smart metering and network re-design can reduce non-technical losses. However, they also demonstrate that the social and political aspects of this problem are often deeply embedded within an economy and will need to be tackled by a wider set of policies. One approach is to initially target large commercial customers; a second is to adopt complementary social measures to mitigate negative sentiment associated with targeting non-technical losses.

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1 Introduction

This project seeks to investigate whether and how the application of emerging technologies and techniques can promote electricity network efficiencies and thereby achieve low carbon development goals.

It is motivated by the importance of access to clean and reliable electricity for human and economic development. Well-targeted programs that promote electricity network efficiency, potentially funded through the International Climate Fund (ICF), could support the Sustainable Energy For All (SE4All) core objective of providing energy that is accessible, cleaner and more efficient. However, the application of new technologies and techniques is often complex due to the context-specific interaction of technical, economic and policy issues. Further, many applications that could drive increased efficiency are poorly understood across the public and private sector, including within development and climate finance communities.

The highest impact opportunities in relation to enhancing network efficiency are likely to be in enhancing understanding of emerging applications and leveraging private finance to drive adoption of those applications. To support these objectives, this report seeks to identify and investigate applications that fulfil four criteria:

- The application is not well understood technically and in terms of the policy and economic barriers that may prevent its application, and so further research and understanding would likely be of benefit to the climate and development communities;
- The application is well placed to leverage private finance;
- The application actively promotes, or at least does not obstruct, ‘leapfrogging’ by facilitating adoption of decentralising technologies, such as storage, distributed generation or smart meters, and innovative business models in electricity supply; and
- The application has clear abatement potential.

Vivid and Arup’s focus for this project is to distil the complexity and breadth of the issues at hand, and thereby assist in the prioritisation of prospective areas for intervention. This report:

- Frames the issues at hand through a broad literature review, that identifies a range of technologies and techniques that could improve network efficiency, and assesses each against the criteria above to identify priority applications for further investigation;
- For these priority applications, it provides a deeper literature review on relevant technical, policy and economics issues and builds on this with case studies to highlight potential barriers and opportunities in relation to implementation; and
- Develops a diagnostic schematic to identify where the priority applications may be most feasible or have the greatest impact.

The remainder of this report sets out each of these elements in turn.

2 Broad literature review

This study is motivated by the importance of access to clean electricity for economic development and climate mitigation and a desire to understand whether and how improvements in network efficiency can promote these goals. The first section of the report will frame and focus this broad issue in three ways:

– By setting out the objectives and context of the analysis;
– By framing a range of potential technologies and techniques that could improve network efficiency within several distinct user contexts to identify a menu of potential applications; and
– By identifying those applications where additional (international public) funding is most likely to have a comparative advantage in supporting knowledge-sharing and leveraging external finance.

2.1 Objectives and context of the analysis

2.1.1 Energy, climate change and development

Improving energy access is essential for economic development. Access to modern forms of energy is a prerequisite for providing clean water, healthcare, sanitation, lighting, cooking, heating and a multitude of other essential services. Both access to electricity (normally measured as proportion of households with a grid connection) and access to non-solid fuels for cooking are strongly correlated with economic development and poverty; countries with high poverty rates invariably suffer from low electrification and heavy reliance on solid fuel (IEA, UNDP, & UNIDO, 2010). For example, recent studies have found that replacing kerosene lamps with solar lanterns offer returns on investment of 15 to 45 times the cost of the lamp (Lighting Africa, 2014). Further, kerosene lamps can greatly increase the risk of respiratory illnesses and lung cancer for users (Apple et al., 2010).

Electrification in many developing countries is still extremely low. The World Bank found that over 1.1 billion people had no electricity connection in 2010 (SE4ALL, 2013). Of this group, 590 million live in Sub-Saharan Africa and another 410 million live in South Asia (SE4ALL, 2013). Connection rates are below 10 per cent in South Sudan, Chad, Liberia, Burundi, Malawi and Niger, with around 85 per cent of the global deficit in electrification concentrated in rural areas (SE4ALL, 2013). Rapid population growth could result in further expansion in this electrification deficit unless widespread action is undertaken to improve access for these underserved communities.

Even consumers who are connected to the grid often experience poor quality service. Among the 83 per cent of the global population with electricity access as conventionally defined, there is extreme variety in the extent to which their needs are served; some consumers enjoy virtually unlimited and completely reliable access to electricity at a reasonable price, while others suffer from frequent and unpredictable outages, unsafe or illegal connections, unreliable voltage or exorbitant prices. For instance, the average Sub-Saharan African firm experiences eight electrical outages a month, losing five per cent of annual sales as a result (World Bank, 2014). Problems are much more severe in some countries than in others; the average Nigerian firm experienced an outage of eight hours around 26 times a month in 2007 (World Bank, 2014). Unfortunately, there is a paucity of data measuring the reliability of the grid in different countries and, as a result, we have an extremely partial picture of the state of electricity access.

The need for improved access to modern energy must take into account the necessity of limiting greenhouse gas emissions. In many instances, these two goals are not in conflict. Improved access to cooking solutions will lead to better health, less deforestation, and lower emissions as consumers switch to more efficient cookstoves and fuels. Renewable power offers the opportunity for greatly expanding electricity access while simultaneously limiting carbon emissions, and are, in many applications and to an increasing extent, a cost-effective alternative to fossil fuels. Nevertheless, interventions should be designed in recognition of the existence of both emissions-intensive and emissions-efficient approaches to many applications.

The development and climate finance donor communities have historically focused on quite separate elements of the issues of energy access and clean energy. Initiatives from the traditional development community often focus on improving access to modern energy through more efficient 'over-the-counter' appliances, particularly cookstoves, or on very small-scale and distributed electricity devices such as 'solar lanterns'. Important but by no means isolated examples of these investments are, respectively, the Global Alliance for Clean Cookstoves and Lighting Africa.

At the other end of the scale of energy investments, multi-lateral development banks have historically made substantial investments in large-scale electricity generation and transmission infrastructure. More recently, these investments have moved away from fossil-fuel based projects and focused on renewable generation sources, but the core approach of funding large-scale energy infrastructure remains. Somewhat paralleling the direction of the multi-lateral development banks, the climate finance community has financed substantial investments in renewable generation, as well as energy efficiency initiatives. The latest estimates suggest that over 80 per cent of bilateral and development finance institution climate finance is directed towards three sectors: renewables, energy efficiency and sustainable transport (Vivid Economics, 2013).

Relatively little attention appears to have been paid to opportunities to enhance network efficiency to complement other investments, despite recent growth in interest. An emerging area of investment in the development community are 'green mini-grids', and hybrid mini-grids. DFID have several ongoing projects, in areas such as Kenya and Somaliland, which are explicitly seeking to encourage hybrid mini-grids. The Climate Investment Funds have also channelled one-quarter of the money available through their Scaling Up Renewable Energy programme into hybrid mini-grids (Climate Investment Funds, 2014). At a larger scale, the World Bank has in recent years funded a series of projects to support investment in, and planning and maintenance of, electricity networks in countries including Ethiopia, Liberia and Sierra Leone. Further aspects of network efficiency, such as use of 'smart grid' technologies are only small elements of the energy access and clean energy investment portfolio. In general, this area is emerging but likely under-explored as an opportunity for investment by the development and climate finance communities.

2.1.2 Investment in network efficiencies presents an opportunity

The relative lack of investments of this type presents an opportunity. There are a number of emerging technologies that could drastically alter the manner in which networks are operated and managed. Recent dramatic reductions in the cost of a range of small-scale renewable generation technologies, particularly solar photovoltaics (PV), and more recently of batteries presents an opportunity to meet energy needs in a more decentralised and flexible manner. Further, 'smart' communication technologies are increasingly being used to monitor and manage both traditional network infrastructure and decentralised mini-grid supply systems.

These technologies could potentially be deployed in developing countries to 'leapfrog' the often inadequate centralised energy supply infrastructure and thereby assist in tackling the significant challenges facing networks in Africa, Asia, Latin America and the Caribbean.

Improvements to network efficiency offer great potential in a range of areas. Transmission and distribution losses (including non-technical losses) among the developing countries of Sub-Saharan Africa are estimated to have averaged 11 per cent in 2011, compared to six per cent in the EU. They were as high as 46 per cent in the Republic of Congo, 28 per cent in Namibia and 24 per cent in Zambia. These losses place a significant burden on generation infrastructure, and they do not begin to quantify the effects of frequent outages on both investments in back-up generation capacity and access to electricity at the consumer end.

Grid improvements can both enable new users to benefit from an electricity connection and increase the quality of service provided to users with a connection. They will be particularly important in ensuring that the significant expected expansion of generating capacity in many developing countries can be delivered and ensure increased user access. At the same time, they can also lead to decreased emissions by displacing fossil fuel generation, both through increasing efficiency and reducing the use of fossil fuel based back-up generators. As a result, they can offer excellent value for money for achieving both energy access and environmental goals.

This report seeks to fill this gap; exploring whether there are high impact opportunities to support emerging technologies and management techniques in network efficiency. Given the scale of the challenge and the relative dearth of material on networks in developing countries, this area has high potential for cost effective interventions that could lead to transformational changes in energy generation, transmission, distribution and consumption.

2.1.3 Defining network efficiency

Electricity network efficiency is a broad concept. In simple terms, it can be anything that uses fewer resources to deliver a certain volume of electricity via a network. Achieving such efficiencies can enhance access, as defined above, by releasing resources to improve reliability, connect new users, or both.

This concept is broad, covering a range of decisions on how to deploy and manage generation, network and storage assets to deliver electricity efficiently. The definition applied throughout this report is broadly an economic concept of efficiency; network efficiency increases if the network is able to provide the same electricity access to its consumers with fewer resources. It is broader than, but encompasses, an engineering understanding of efficiency, which focuses on the extent to which energy is lost between generation and consumption. One engineering definition of network efficiency is the ratio between recorded electricity consumption and electricity generated. Losses during transmission and distribution can be broken down into technical and non-technical categories. Technical losses reflect physical losses in transport between generation and consumption. Non-technical losses reflect that not all electricity consumed is paid for.

Reflecting the breadth of this concept, electricity network efficiency can be enhanced using a range of technologies and techniques. These can range from 'conventional' augmentation or enhancement of generation or network assets to deliver power in a more cost-effective and efficient way, to a range of emerging technologies.

2.2 User contexts, technologies and potential applications

The challenges and opportunities relating to energy access vary based on context. A particularly important contextual factor defining the menu of potential interventions is user context. Users, including residential, commercial and industrial consumers, can be roughly divided into three groups:
- grid-connected;
- not grid-connected but near existing infrastructure (‘near-grid’); and
- in a remote location far from existing network infrastructure.

While a wide range of contextual factors are important, the proximity to network infrastructure radically changes how each technology could be deployed to improve network efficiency. For instance, smart meters could have different uses and implications as part of a national grid than in the context of an off-grid mini-grid. In the context of a national grid, smart meters might be used to identify and manage power theft, or to transmit time-varying price signals to consumers to manage their impact on the collective network. Within a mini-grid, a smart meter would be more likely to be used to provide consumers with information to allow them to ration the available power for high priority needs.

These three user contexts can be combined with a list of techniques and technologies to yield a set of potential interventions to improve network efficiency. There are five key technologies and techniques that are considered in this report, which jointly cover the breadth of potential interventions to improve network efficiency:
- Network transmission and distribution assets;
- Generation assets;
- Storage;
- Smart meters and other smart ICT devices; and
- Operation, maintenance and planning.

Network transmission and distribution assets encompass all the conventional technologies used to transmit electricity from generation to consumption over distance. This includes high-voltage transmission lines, low-voltage distribution lines, transformers that change voltage between these stages or, in the case of high voltage direct current connections, converter stations. In one extreme, these assets can be used to connect one large scale grid to another. At the other extreme, they can be used to extend grid coverage to nearby, unconnected consumers.

Generation assets encompass all large and small scale generation technologies, such as coal-fired power plants, wind farms, solar photovoltaics and diesel generators. For grid-connected consumers, these technologies could be implemented through either large-scale centralised generation or through smaller scale distributed generation located closer to demand. For more remote consumers, generation assets are likely to be deployed either as a stand-alone power source or as part of a mini-grid.

Storage includes all assets which can be used to temporarily store electricity for use at a later point. For grid-connected areas this can be in the form of large-scale storage facilities. In practice, the vast majority of large-scale storage is provided by pumped hydro. It can also take the form of distributed storage, either controlled by utilities or used in conjunction with a grid-connected mini-grid. For remote or near-grid users, it is more likely to take the form of distributed storage; small-scale storage, typically using batteries, is often essential within mini-grid systems that use local renewable energy sources to manage intermittency.

Smart meters and other smart ICT devices include all infrastructure that facilitates the communication of close to real-time information on network use and performance. These devices can involve information flow from utilities to consumers, consumer to utilities or in both directions. The variety of approaches these technologies can facilitate is substantial and includes time-of-use pricing for consumers, monitoring consumption to reduce non-technical losses, facilitating utility control of load from particular appliances, and adaptive management of grid assets to manage outages or reduce technical losses.

Operation, maintenance and planning encompasses a range of management techniques to better operate, maintain and plan existing or new energy assets. Improved practices in these areas are likely to be able to improve network efficiency in a range of ways. Better maintained generation or network assets will use less fuel or cause fewer losses in delivering a given volume on electricity. Better operation or planning of the grid could allow for a more efficient dispatch of existing assets in the short-term, or investment in a more efficient asset mix over the long-term. Many developing countries may lack the technical capacity to operate, maintain and plan energy networks to a high standard.

The combination of technologies and contexts suggest fifteen separate potential applications. These applications are shown in Table 1. Some technologies are applied in combination within a single application. For example, a mini-grid can consist of distributed generation, storage and various smart technologies.

Table 1. **A matrix of technologies and contexts suggests fifteen distinct applications**

Technology or technique	Grid-connected	Unconnected near-grid	Unconnected remote rural
Network assets	Grid-to-grid interconnection (#1)	Conventional grid extension (#2) Grid extension augmented with smart technologies (#3)	N/A
Generation assets	Large-scale centralised generation (#4) Distributed generation (#5) Grid-connected mini-grid (#6)	Grid extension augmented with smart technologies (#3) Off-grid mini-grid (#7)	Off-grid mini-grid (#7)
Storage	Grid-connected mini-grid (#6) Large-scale storage (#8) Decentralised storage (#9)	Grid extension augmented with smart technologies (#3) Off-grid mini-grid (#7)	Off-grid mini-grid (#7)
Smart meters and other smart ICT devices	Grid-connected mini-grid (#6) Smart metering and ICT for demand side response (#10) Direct load control and smart appliances (#11) Smart metering and ICT to address non-technical losses (#12) Outage management and grid management (#13)	Grid extension augmented with smart technologies (#3) Off-grid mini-grid (#7)	Off-grid mini-grid (#7)

Technology or technique	Grid-connected	Unconnected near-grid	Unconnected remote rural
Operation, maintenance and planning	Technical assistance – operations and maintenance (#14) Technical assistance – planning and system balancing (#15)	N/A	N/A

Note: *The numbers in parentheses sequentially identify 15 unique applications to be referred to throughout the literature review. Where a single application can use multiple technologies in combination, the number is repeated for each technology that is relevant to that application. Issues relating to operating, maintenance and planning of new assets is assumed to be integrated with the investment in the assets themselves, although in practice this may occur to varying extents and with varying degrees of success.*

Source: *Vivid Economics and Arup*

A broad description of the fifteen applications is provided in Table 2.

Table 2. **Overview of fifteen applications**

Application	Description	Controlling entity	Purpose
(#1) Grid-to-grid interconnection	High voltage interconnection of separate large-scale grids	Utilities	Power flows between grids will potentially increase their stability and reliability and reduce generation costs
		Merchant investors	Earning revenue from trading electricity between grids, either by contract or through arbitraging price differences
(#2) Conventional grid extension	Extension of distribution network to supply electricity to new users	Utilities	Extension of access or replacement of higher cost small-scale mini-grid power
(#3) Grid extension augmented with smart technologies	As for (#2) but augmented with storage, distributed generation and/or control systems	Utilities	As for (#2) but potentially at lower cost due to reduced transformer and line ratings, and reduced line losses
(#4) Large-scale centralised generation	Bulk supply of electricity from large-scale generators connected to the high voltage transmission network for transport and sale to customers	Utilities	To satisfy electricity customer demand and earn revenue from electricity sales
		Independent power producers (IPPs)	To earn revenue from wholesale electricity sales to a utility or power pool
(#5) Distributed generation	Small-scale generation sources connected 'deep' within the electricity grid close to end users	Power users	To substitute for grid power and avoid grid charges
		IPPs	To earn revenue from wholesale electricity sales to a utility, power pool or direct to a power user. Distributed generators can also earn revenue from network support services
		Utilities	As for (#4). In addition, distributed generation can substitute for and reduce spending on network assets

Application	Description	Controlling entity	Purpose
(#6) Grid-connected mini-grids	A system using local generation, control systems and/or storage to supply end-users with electricity either in combination with the grid, or in 'island-mode' when the grid is unavailable	Power users (or third parties on contract to users)	Power users can potentially obtain more reliable and/or cheaper electricity than available from the grid through use of localised energy sources
(#7) Off-grid mini-grids	A system supplying one or more users using local generation, control systems and/or storage to supply end-users with electricity in the absence of a grid-connection	Power users (or third parties on contract to users)	To provide electricity access in the absence of a grid connection
		Utilities	As a cheaper alternative to providing access through a grid connection
(#8) Large-scale storage	A system for the large-scale storage of electrical energy for later use, connected to the high voltage transmission network	Utilities	To balance the grid by storing energy at times of low demand relative to supply for use at times of high demand or constrained supply
		IPPs	To arbitrage price fluctuations in power pools caused by changing demand conditions, thereby incidentally assisting to balance the grid
(#9) Decentralised storage	A small energy storage system connected to the low voltage distribution network	Utilities	As for (#8). In addition, decentralised storage can substitute for and reduce spending on network assets
		Power users	To enhance reliability by providing back-up power at the consumer's premises. User adoption of batteries is commonly combined with distributed generation, and so is considered as part of (#6) for the purpose of this study
(#10) Smart metering and ICT for demand side response	Use of 'smart' electricity meters that record electricity use in small intervals and/or devices to inform users about their electricity use	Utilities	By recording energy use in small periods, smart meters can support pricing structures that encourage reduced use at peak times. Smart meters can also reduce costs through remote reading and disconnection. Other ICT devices, often in combination with smart meters, can support demand side response by informing users about their electricity use and prevailing prices, or requesting them to reduce demand
(#11) Direct load control and smart appliances	Use of remotely controlled devices to control load (demand) of particular appliances	Utilities	Utilities can constrain or defer demand from appliances at peak times, or restrict use to off-peak times, to reduce peak loads and improve grid management
(#12) Smart metering and ICT to address non-technical losses	Use of remotely read 'smart' meters to record electricity use at a premises and/or within a geographic area	Utilities	Additional information from smart meters can identify and help reduce non-technical losses theft, increasing utilities' revenues
(#13) Smart metering and ICT for outage and general grid management	Smart meters and other ICT devices, including user mobile phones, can assist to identify outages. More advanced devices can 'self-heal' faults through adaptive behaviour and minimise the effect of outages through rapid isolation	Utilities	Reduced impact of outages through prevention (through adaptive behaviour), reduction of scale (through rapid isolation), or more rapid corrective response on the ground (through faster notification and more precise geographic location)

Application	Description	Controlling entity	Purpose
(#14) Supply-side technical assistance – operations and maintenance	Improving the operations and maintenance of grid assets through technical assistance	Utilities	Overcoming technical capacity limitations to enhance grid reliability and/or reduce costs
(#15) Supply-side technical assistance – planning and system balancing	Improving planning and system balancing functions of grid operation through technical assistance	Utilities	Enhancing grid reliability in the short-run by improved management of generation assets (grid balancing) or in the longer-run through improved planning and integration of generation and network assets

Note: *Some definitions require that a 'mini-grid' supply more than one user. In relation to applications (#6) and (#7) we have broadened this definition to include systems that supply only one user on the grounds that the technical characteristics of these systems are similar and they can be grouped together for the purpose of this analysis.*

Source: *Vivid Economics and Arup*

2.3 Key applications

Given the breadth of technologies available to enhance network efficiency, this report seeks to identify and focus on several particular promising approaches. There are many ways capital could be invested in electricity networks in developing countries. Centralised approaches to system planning and investment are in general well understood and the critical factor in their implementation is sufficient capital and technical capacity. As is discussed in section 2.1.1 the development and climate finance communities have implemented a range of investments of this type over past decades. These investments, though undoubtedly worthwhile, are not the focus of this study. Rather this report focuses on possible new areas for investment that can complement more 'conventional' investments to support the overall objective of access to clean, reliable electricity. Accordingly we prioritise applications using four criteria:

– Whether the application is well understood technically and in terms of the policy and economic barriers that may prevent its application;
– Whether the application is well placed to leverage private finance;
– Whether the application actively promotes, or at least does not obstruct, 'leapfrogging' by facilitating adoption of decentralising technologies, such as storage, distributed generation or smart meters, and/or innovative business models in electricity supply; and
– Whether the application has clear abatement potential.

The first criterion is designed to identify areas which are less well understood, both in terms of the underlying technology and the scope of its deployment, as such areas are more likely to benefit from further research. In such areas, concessional funding or other support has a greater chance of driving substantial improvement in network efficiency, such as through learning and demonstration effects.

The second criterion is designed to focus on areas where additional private finance might be likely to be leveraged by public support. Given the relatively limited funds available from public sources, it is important that they are invested in areas which have the potential to lead to further investment through the private sector. This greatly amplifies the potential impact of funding, and can lead to relatively small investments having potentially transformational impacts on energy systems over the medium to long-term. A particular issue in relation to this criterion is the ability of 'traditional' utilities in developing countries to set cost-reflective tariffs. This can occur due to both the low-income of users and political concerns about energy costs. Understandably, private financiers are often reluctant to provide capital to these entities. Further, even when these utilities have the opportunity to make specific investments with strong rates of return, these returns may simply cross-subsidise other loss making activities within the utility. Although this description is not true in all cases, it means that investments that rely on finance from an incumbent utility (comprising at least the network and often also the generation and retail elements of the supply chain) will, in general, face more difficulties in raising private finance. By contrast where energy users and suppliers can make investments without the returns being intermediated by the incumbent utility, the prospects of attracting new private finance to these activities is higher. This is particularly the case where there is a diverse range of flexible and innovative private-sector technology suppliers.

The third criterion is designed to capture the potential to overcome the inherent limitations of conventional centralised approaches to power supply. These conventional approaches tend to have two key challenges: first they are often unable to reflect the different needs and willingness to pay of different energy users; second they are not well suited to promoting innovation amongst a diversity of suppliers. A key reason why decentralised technologies offer a potential 'leapfrogging' paradigm shift in this space is not that they provide an inherently superior level of service, but rather that the dynamics of innovation and implementation may better promote user needs where capital and/or technical capacity are limited. Though the analogy is not perfect, this is consistent with the more decentralised adoption of mobile telecommunications in developing countries, compared to the relative failures of 'traditional' fixed-line telephony in those same markets.

The fourth criterion is designed to identify applications that are compatible with environmental and climate sustainability. There is a growing consensus that, while increased energy access is essential, it must be promoted in a manner that is compatible with environmental and climate goals. Priority areas for investment should not only have the capacity to achieve development impacts, but also do so in a manner that limits environmental cost.

On the basis of a preliminary literature review, each of the fifteen technologies are graded as high, moderate or low on the basis of the four criteria. Priority areas need to be rated as high or moderate on all four indicators. The basis for grading each indicator is described in Table 3.

Table 3. **Priority applications are assessed against four criteria**

Rating	High	Moderate	Low
Value from further research	The application is not well understood and has rarely been applied in developing countries; and so further research is likely to offer substantial value to the development and climate finance communities	The application is fairly well understood but delivery examples in developing countries are limited	The application is well understood and has been widely applied in developing countries; and so further research is not likely to offer substantial value to the development and climate finance communities

Rating	High	Moderate	Low
Ability to leverage private finance	The activity will dramatically improve the financial position of an incumbent utility or can be flexibly undertaken by users and suppliers in a decentralised manner	The activity will only moderately improve the financial position of an incumbent utility or can be indirectly financed by an incumbent utility (e.g. through a power purchase agreement)	The activity will make only marginal improvements to the financial position of an incumbent utility and cannot be easily pursued between individual users and a diversity of suppliers
Leapfrogging potential	Actively promotes adoption and use of decentralising technologies or innovative business models in electricity supply	Weakly promotes adoption of decentralising technology that might, in future, support innovative business models in electricity supply	Does not promote decentralising technology or innovative business models
Abatement potential	The application has strong potential to directly reduce emissions	The application is likely to promote reduced emissions, though it may do so indirectly through supporting increased use of low-carbon technologies or promoting a more efficient use of existing generation assets	The application is unlikely to substantially reduce emissions

Source: Vivid Economics and Arup

Table 4 shows the performance of the fifteen technologies identified in Table 1 versus each of the four criteria. The judgement against each criteria is based on a broad literature review, which has covered a wide variety of both peer reviewed academic literature and grey literature on each technology and technique. It also draws upon the extensive experience of both Arup and Vivid Economics on the engineering and economics of electricity networks. The literature surveyed is recorded in Appendix B, which can also serve as a useful reference point for readers seeking more information on any of the technologies or techniques discussed.

Table 4. **Performance Assessment of each technology and technique against four criteria suggests four areas of focus within this study**

Application	Value from further research	Ability to leverage private finance	Leapfrogging potential	Abatement potential
(#1) Grid-to-grid interconnection	Low. The technological aspects are well understood, with large interconnectors already in operation in Europe, North America and a range of developing country contexts. For example, a 500 MW high voltage direct current interconnector was recently constructed between Bangladesh and India.	Moderate, and context dependent. Constructing 'merchant' (i.e. private for profit) interconnection is possible but is a complicated investment even in developed countries. Several merchant interconnectors have opted to become regulated and financed as part of the general asset base of network utilities.	Low. Interconnection is a core element of traditional centralised power supply. By diverting substantial resources to support a traditional supply model, it may impede 'leapfrogging' to more decentralised and flexible approaches.	Moderate, but highly dependent on network design. Interconnection can improve network efficiency by improving load factor. Abatement outcomes depend on relative emissions intensities of connecting grids and net flows.
(#2) Conventional grid extension	Low. Grid extension has been the typical approach to improving electricity access in both developed and developing countries for decades.	Moderate. Grid connection can provide additional revenues through enabling sales to new consumers, but these revenues will typically accrue to the incumbent utility player(s). Unless this extension is highly cost-effective, these additional revenues are unlikely to attract additional private investment to the sector.	Low. Grid connection is the standard means of providing access to electricity in a traditional centralised power supply system, both in developed and developing countries.	Low. Potentially, if the grid has low carbon intensity and the connection displaces inefficient diesel generation, emissions could be reduced. However, in most cases total energy consumption would expand and emissions are likely to rise.
(#3) Grid extension augmented with smart technologies	High. Smart technologies to manage demand, generation and storage could decrease the cost of grid extension and enable advanced control methods. This approach to improving the economics of grid extension has not been fully explored, nor have these technologies been widely deployed in developed or developing countries.	Moderate. As for (#2) above, grid extension can provide additional revenues, but is likely to be captured by utilities and is unlikely to leverage further private investment.	Moderate. Adopting smart technologies to augment grid extension would represent a more decentralised supply model, but it is still ultimately reliant on a conventional centralised approach.	Moderate. Where renewable distributed generation is used, this approach is likely to be less emissions-intensive than centralised supply. Further, distributed generation can potentially reduce network losses, decreasing demand for centralised electricity generated using fossil fuels.
(#4) Large-scale centralised generation	Low to moderate. There are some emerging technologies (such as carbon capture) and many other technologies that are still undergoing rapid cost reductions (such as solar PV). However, from a network efficiency perspective, the use of centralised generation to meet power needs is well understood.	Moderate to high, but context dependent. In more liberalised market structures, generation investments can leverage private finance, but in more state-dominated sectors investments are ultimately underpinned by power purchase agreements with the incumbent utility, and therefore may be constrained by that entity's credit-worthiness. There are also potential demonstration and learning effects from early projects applying emerging generation technologies in contexts where they are not widespread. This may crowd in private finance.	Low. Centralised generation transmitted and distributed using a large scale grid is a critical element of the traditional centralised electricity supply model.	Moderate and dependent on the generation technology. Increased generation with low carbon infrastructure may significantly reduce emissions if it displaces high carbon infrastructure, such as centralised generation with fossil fuels or decentralised generation with diesel.

Application	Value from further research	Ability to leverage private finance	Leapfrogging potential	Abatement potential
(#5) Distributed generation	Low to moderate. The technical issues that arise from connecting distributed generation, and the various generation technologies themselves, are well understood. New, smart technologies are emerging that can assist with management of distributed (often intermittent) generation, but these are more typically part of 'mini-grid' approaches discussed below.	Moderate, but context dependent. As with (#4) above, in more state-dominated sectors investments are ultimately underpinned by power purchase agreements with the incumbent utility, and therefore may be constrained by that entity's credit-worthiness. If the distributed generation is intended to defer network investment, this value must typically be financed by the incumbent network company.	Moderate. Distributed generation, in the absence of mini-grid technologies, typically relies on grid connection to either export power or to complement the distributed generation. Further benefits of distributed generation include reducing network losses or moderating peak demand on network assets. Although these benefits represent a more decentralised approach to energy supply, they typically are integrated with and reliant on the centralised grid.	Moderate and dependent on the generation technology. Increased generation with low carbon infrastructure may significantly reduce emissions if it displaces high carbon infrastructure, such as centralised generation with fossil fuels or decentralised generation with diesel.
(#6) Grid-connected mini-grids	Moderate. Technical issues around grid-connected mini-grids moving between 'islanded' and grid-connected mode are moderately well understood. The component parts of grid-connected mini-grids, principally distributed generation, storage and demand management systems are generally well understood given the substantial range of investments in mini-grids in recent years. An emerging, but generally poorly understood, practice is using batteries to complement or replace back-up diesel generation.	Moderate to high. Users that are connected to an unreliable grid may invest their own capital to enhance power reliability through mini-grid approaches. Further, there are numerous suppliers of this type of infrastructure, meaning that private capital is generally available for development and deployment of these approaches.	Moderate to high. Although the user remains reliant in part on the centralised grid, the development of a grid-connected mini-grid utilises smart, decentralised technologies to complement, and ultimately take pressure off, the centralised grid and supply power in a more flexible manner.	Moderate. Mini-grid technologies typically use some distributed renewable generation, which both displace fossil-fuel generation and can reduce network losses.
(#7) Off-grid mini-grids	Moderate. A diverse range of entities have developed technical solutions in this space in recent years. Awareness of, and innovation in, the potential use of smart technologies to address energy access issues appears high. However, some technical, policy and economic issues related to mini-grids are not as well understood. There are few examples of mini-grids being constructed with eventual grid-connection in mind ('grid-ready mini-grids'), and little understanding of the policy frameworks that could be used to encourage grid-readiness.	High. Mini-grids have significant potential to encourage private investment in energy infrastructure, by allowing third party operators to create small-scale grid systems to serve rural customers. Smart technologies can improve the performance of mini-grids, keeping costs down and increasing their profitability for private investors. Further, mini-grids typically expand access and so attract new revenues to the sector. By explicitly addressing commercial as well as technical issues around future grid-connection, grid-ready mini-grids can 'future-proof' investments in these assets and further attract private finance.	High. Mini-grids typically adopt smart technologies to develop a highly flexible and decentralised model of electricity supply. These approaches explicitly seek to leapfrog the traditional centralised model of electricity supply.	Moderate and dependent on generation technology. Smart technologies are particularly useful for managing hybrid systems incorporating both renewable and fossil-fuel based generation, and are therefore well-placed to encourage abatement through use of renewable generation.

Application	Value from further research	Ability to leverage private finance	Leapfrogging potential	Abatement potential
(#8) Large-scale storage	Moderate. The vast majority of large-scale storage occurs through pumped-storage hydroelectricity. This technology is well understood and is widely deployed. Other emerging technologies, such as compressed air storage or large-scale batteries, are rarely deployed and less well understood from a technological standpoint.	Low. In highly advanced market structures, it is possible for large-scale storage to emerge on a commercial basis to arbitrage price fluctuations in the wholesale market. However, this behaviour is rare, even in sophisticated, long-standing power pools in developed countries. In more centralised market structures, investment in large-scale storage would be reliant on funding through the incumbent utility.	Moderate. Centralised storage ultimately is used to balance and support a centralised grid. Although it can assist with the integration of emerging (e.g. renewable) technologies, it principally operates in a conventional centralised supply model.	Moderate. By allowing fossil-fuel generation to be run more efficiently and by enabling greater use of intermittent renewables, storage could decrease emissions from electricity production.
(#9) Decentralised storage	High. Decentralised storage can be used by utilities to enhance grid reliability. Storage located closer to demand can be intelligently controlled through smart technologies to reduce spending on network assets such as transformers. These technologies are being trialled in developed countries but are generally poorly understood; few examples of decentralised storage are currently available.	Low. Where decentralised storage is used for network support it will principally earn a return by displacing alternative investments by the utility in grid infrastructure. The utility forms the most likely funder of both the storage facility itself and the smart network technology required to operate the storage. Evidence suggests that, while decentralised storage controlled by users can attract private finance, these applications are often combined with other power supply elements and so are grouped within application (#5) for the purpose of this study.	Moderate. Decentralised storage effectively displaces network assets, and so represents a clear move to a decentralised form of electricity supply. However, in the absence of distributed generation (i.e. a mini-grid) it remains reliant on, and designed to support the operation of, conventional grid approaches.	Moderate. Decentralised storage could marginally reduce losses by reducing demand on network assets at peak times. It could also reduce emissions by enabling greater use of intermittent renewables.
(#10) Smart metering and ICT for demand side response	Moderate. Smart metering technologies are well understood and straightforward to apply. An emerging range of other ICT devices to inform consumers about electricity use are less well understood. The political, economic and behavioural aspects of these applications are less well understood, with some experiences in developed countries but few in developing countries. Applications that rely on consumer information rather than price incentives to motivate behaviour change are particularly poorly understood.	Low. Roll-out of smart meters is typically financed by centralised utilities as the range of benefits is difficult to capture by a single party. Similarly, where the purpose of ICT to inform consumers is to reduce load at peak times and assist with grid balancing, the associated systems would likely be utility funded. Accordingly, investment in this approach is essentially dependent on traditional sources of utility capital.	Moderate. Smart meters and other ICT devices are an important component of a decentralised electricity grid, but applied in isolation represent only a moderate step towards a 'leapfrogging' supply model.	Context dependent. Shifting demand between high demand and low demand times has an ambiguous emissions outcome. Abatement is not guaranteed, in the absence of broader energy efficiency efforts.
(#11) Direct load control and smart appliances	Moderate. Direct load control has been implemented in various countries for many years in particular contexts, for example in relation to electric water heaters. Emerging areas such as controlling air-conditioners, refrigerators and other devices, are less well understood. Approaches not based on direct control or 'set and forget' bases for intervention are not as well understood, but are covered in application (#10).	Low. Direct load control enables better grid management by the utility, but does little to encourage investment. When coupled with advanced metering technology, it may be used to incentivise consumers to monitor and cut down on their electricity usage. This, in turn, may encourage investment in energy efficient appliances.	Moderate. Interaction between users (appliances) and the utility is likely to be a feature of a future decentralised electricity grid. However, in isolation it represents a moderate step towards 'leapfrogging' and most applications considered are focused on supporting traditional centralised networks.	Context dependent. Shifting demand between high demand and low demand times has an ambiguous emissions outcome. Abatement is not guaranteed, in the absence of broader energy efficiency efforts.

Application	Value from further research	Ability to leverage private finance	Leapfrogging potential	Abatement potential
(#12) Smart metering and ICT to address non-technical losses	Moderate. Smart metering and remote monitoring technologies are well understood and straightforward to apply. Potential political and institutional barriers to implementation include a lack of appropriate loss-reduction incentives, especially in state-run utilities, and opposition within utilities from those benefiting from collusion with customers. These are reasonably well documented, but are complex and context dependent and so additional investigation may be of value.	Moderate. Investments of this type must typically be financed from the operating budget of the utility. However, evidence suggests that successful programmes of this type often substantially improve the financial position of the utility, with consequent scope to leverage private finance.	Moderate. Smart meters are an important component of a decentralised electricity grid, but applied in isolation represent only a moderate step towards a 'leapfrogging' supply model.	Moderate. Reduction of non-technical losses through smart metering will result in fewer consumers able to access electricity at no cost. In the short term reductions in thefts will reduce energy consumption directly, and effective metering will ensure these customers face the energy use reduction incentive caused by bearing the cost of purchasing electricity.
(#13) Smart metering and ICT for outage and general grid management	High. Smart metering technologies are well understood and straightforward to apply. Other technologies such as advanced voltage control or remote management of grid outages, are emerging and less well understood. SMS systems to improve communication of planned outages to consumers and to enable communication of unplanned outages to utilities, have been applied in some developing countries and have scope to be extended. In general, this is a complicated and rapidly changing area of technology.	Low. Investments of this type are dependent on traditional utility finances, and will face competition from other uses of capital. Evidence suggests that projects of this type have often been reliant on public sources of funding and will not generally be offer sufficient returns to significantly alter the ability of utilities to attract private finance.	High. Smart technologies of this kind will be essential to the efficient management of more decentralised energy supply options. Accordingly, they have high potential to support 'leapfrogging' electricity supply models.	Low to moderate. Advanced voltage control can reduce losses, though this effect is fairly small compared to the reliability benefits and the cost of implementation. Similarly, applying SMS to improve communication, data collection and management is primarily useful as a means to improve quality of service to consumers, rather than reduce emissions/
(#14) Supply-side technical assistance – operations and maintenance	Low to moderate. The technical aspects of operating and maintaining a grid are generally well understood, as is the absence of technical capacity in some markets and the implications for grid reliability and efficiency. Policy and economic barriers to engaging technical assistance to address these issues are moderately well understood.	Moderate. Investments of this type must typically be financed from the operating budget of the utility. However, depending on the scope for improvements in operations and maintenance practices, the financial position of the utility could improve sufficiently to facilitate further investment, including leveraging private finance.	Low. This approach attempts to operate a conventional supply model more efficiently and effectively, rather than develop alternative 'leapfrogging' approaches.	Moderate. Better maintenance of network assets contributes to reductions in technical losses.

Application	Value from further research	Ability to leverage private finance	Leapfrogging potential	Abatement potential
(#15) Supply-side technical assistance – planning and system balancing	Moderate. The technical aspects of planning and balancing a grid are quite well understood, albeit highly complex. The absence of technical capacity in some markets is likely to be a barrier to grid reliability and efficiency. Policy and economic barriers to engaging technical assistance to address these issues are moderately well understood.	Moderate. Investments of this type must typically be financed from the operating budget of the utility. However, depending on the scope for improvements in planning and system balancing, the financial position of the utility could improve sufficiently to facilitate further investment, including leveraging private finance.	Low to moderate. This approach generally attempts to operate a conventional supply model more efficiently and effectively, rather than develop alternative 'leapfrogging' approaches. However, system balancing techniques may assist in the integration of decentralised generation and storage sources. Further, improved system planning may assist in identifying where decentralised supply options, such as distributed generation, are more cost-effective than centralised generation supported by investment in network assets.	Moderate. System balancing may assist in the integration of intermittent renewables, supporting lower-emissions generation. Enhanced system planning could reduce network losses.

Source: *Vivid Economics*

A summary of the findings for each of the technologies, in terms of their performance against each of the four criteria, is provided in Table 5. An area is identified as a priority if it performs at least moderately well in all four criteria.

Table 5. **Four priority applications for this study are identified based on the criteria**

Application	Value from further research	Ability to leverage private finance	Leapfrogging potential	Abatement potential	Overall assessment
(#1) Grid-to-grid interconnection	✘	~	✘	~	✘
(#2) Conventional grid extension	✘	~	✘	✘	✘
(#3) Grid extension augmented with smart technologies	✓	~	~	~	✓
(#4) Large-scale centralised generation	✘	✓	✘	~	✘
(#5) Distributed generation	✘	~	~	~	✘
(#6) Grid-connected mini-grids	~	✓	✓	~	✓
(#7) Off-grid mini-grids	~	✓	✓	~	✓
(#8) Large-scale storage	~	✘	~	~	✘
(#9) Decentralised storage	✓	✘	~	~	~
(#10) Smart metering and ICT for demand side response	~	✘	~	~	✘
(#11) Direct load control and smart appliances	~	✘	~	~	✘
(#12) Smart metering and ICT to address non-technical losses	~	~	~	~	✓
(#13) Smart metering and ICT for outage and general grid management	✓	✘	✓	~	~

Application	Value from further research	Ability to leverage private finance	Leapfrogging potential	Abatement potential	Overall assessment
(#14) Technical assistance – operations and maintenance	✘	~	✘	~	✘
(#15) Technical assistance – planning and system balancing	~	~	✘	~	✘

Note: *Ratings are based on the criteria outlined in Table 3.*

Source: *Vivid Economics and Arup*

There are four applications that merit further investigation, based on the arguments provided above. These are:

– Grid extension augmented with smart technologies;
– Grid-connected mini-grids;
– Off-grid mini-grids utilising smart technologies; and
– Smart metering and ICT to address non-technical losses.

The next section will consider each of these areas in turn, covering the relevant literature in more depth and providing case studies to illustrate the potential impact of each technology, predominantly drawn from developing country contexts.

Two further applications are identified as areas for potential future investigation in other studies based on receiving only one ‘low’ ranking across the four criteria, whilst ranking highly against at least one other criterion. These applications are:

– Decentralised storage; and
– Smart metering and ICT for outage and general grid management.

These applications are not identified as priority applications primarily on the grounds that they may not be well placed to leverage private finance. Therefore it is less likely that these applications are presently capable of achieving substantial improvements in network efficiency in the context of capital constrained developing country utilities. However, further technological development in these areas (likely to be driven by trials by developed country utilities) and dissemination of information on these applications can support future developing country adoption. The timeframe for this adoption will depend in large part on the level of financial support made available and local technical capacity.

3 Analysis of priority applications

This section discusses the four priority applications in turn incorporating the following elements:

– A brief overview, with more detail on some technical aspects of the application provided in Appendix A;
– A series of case studies; and
– Conclusions drawn from the group of case studies.

Table 6 shows the case studies examined by application, location and country income.

Table 6. **Distribution of current case studies by application, location and country income**

Location	**Income group**	**Grid extension augmented with smart technologies (application #3)**	**Grid-connected mini-grids (application #6)**	**Grid-ready mini-grids (within application #7)**	**Smart meters and ICT to address non-technical losses (application #12)**
Developed world	HIC	Orkney Islands smart grid (Scotland) Peak shaving in American distribution networks (United States)	-	-	-
Africa	LIC	-	Mwenga hydro plant and mini-grid (Tanzania)	-	-
Africa	MIC	-	Batteries to support solar-powered ATMs (Lagos, Nigeria) Battery to support petrol stations (Nigeria)	-	-
Asia	LIC	-	-	-	-
Asia	MIC	-	DESI Power (India) Mini-grid for cotton mill (India) Telecom towers with battery storage (India)	Darewadi mini-grid (Maharashtra, India) Athureliya community village (Sri Lanka) Sagar Island, (West Bengal, India)	Smart metering and ICT in North Delhi (India)
LAC	LIC	-	Solar power and battery storage to support hospital (Cap-Haitien, Haiti)	-	-
LAC	MIC	-	-	-	Ampla smart meters (Rio de Janeiro, Brazil) Edesur (Dominican Republic)

Note: *Income classification is based on the World Bank lending groups*

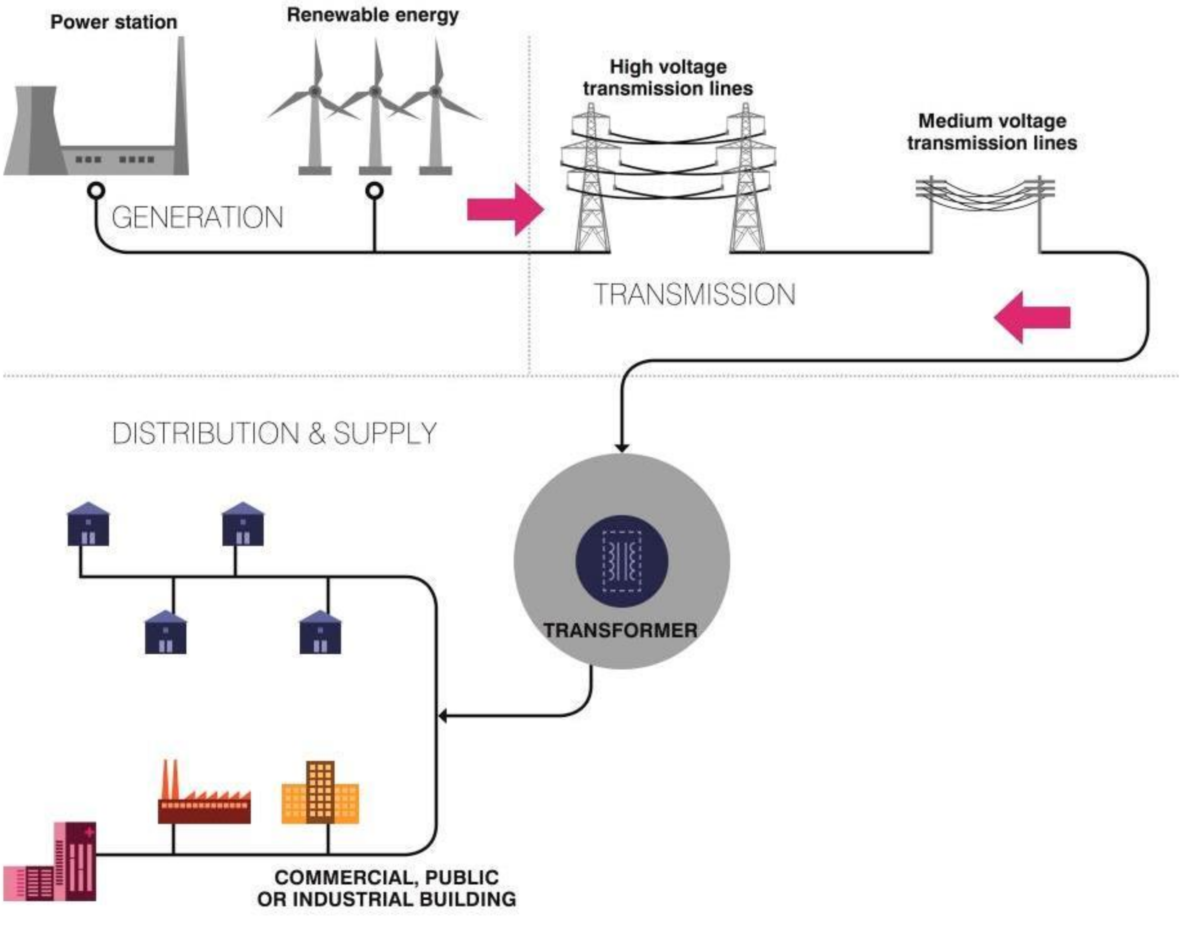
Source: *Vivid Economics*

3.1 Grid extension augmented with mini-grid technologies (Application #3)

3.1.1 Application overview

'Traditional' approaches to extending the electricity network to unconnected peri-urban or rural areas typically involves transmission and distribution poles/towers, cables, transformers, switchgear and some form of system to monitor and control the network. These components are designed to operate together to deliver reliable power to the new customers within specified voltage and frequency limits while maintaining the stable operation of the existing system. This approach is illustrated in a stylistic fashion in Figure 1.

Figure 1. **Stylised depiction of a traditional centralised grid extension**



Source: Arup

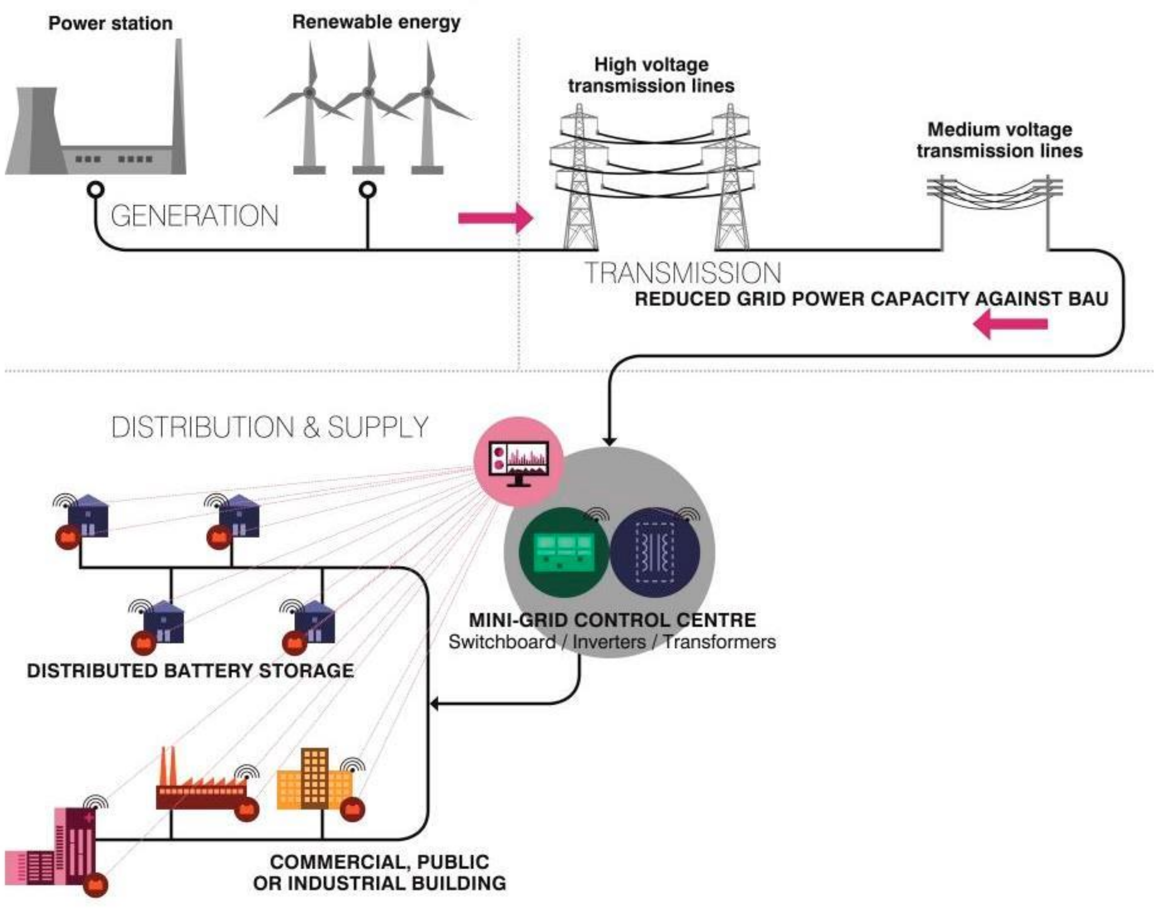
Potentially a range of smart distributed technologies could be employed to augment such a traditional grid connection, while improving the economics and/or reliability of the grid extension. These technologies could include:

– Distributed storage;
– Distribution automation or 'advanced network management' technologies, including voltage control, dynamic line and transformer rating, and thermal congestion analysis;
– Distributed generation integrated with network control elements; and
– Demand management techniques or technologies;

(see Appendix A for more detail).

These approaches can all potentially improve grid extension economics by reducing the required capacity of new lines, transformer and switchgear for the extension, and potentially the scope and cost of upgrades of the network upstream of the new network assets. This approach is illustrated in Figure 2.

Figure 2. **Stylised depiction of a grid extension supported by smart technologies on the demand side**



Source: Arup

The benefits and the associated costs of employing smart technologies in this way need to be considered on a case-by-case basis. In general, while some of these approaches are less capital intensive than traditional network extension, they are likely to impose additional operational and maintenance costs.

Grid extension, whether 'traditional' or augmented with smart technologies, is a complex planning exercise that requires careful analysis. A range of design factors can lead to poorly specified investments, including estimating demand, topographical constraints, network operating constraints, limited technical capacity and difficulties associated with balancing load and renewable generation.

3.1.2 Case study analysis

Vivid Economics and Arup were unable to identify case studies that directly addressed this application, in which the costs of grid extension are reduced and/or its performance improved through applications of various smart distributed technologies. As discussed above, these technologies range from distributed generation and storage to more complex systems for distribution automation.

However, we were able to identify two case studies where similar 'smart' technologies were applied to avoid costs associated with upgrading the existing grid. These applications are analogous to application #3 in that smart technologies are used to substitute for and reduce the cost of traditional fixed line network infrastructure, as well as potentially enhancing the operation of that network. The case studies are described briefly below and in more detail in Appendix B.

The first case study involves advanced system management techniques by a Scottish power utility to integrate increased renewable generation in the Orkney Islands, whilst avoiding network augmentation. Technologies employed in this case study include real-time generation control, dynamic line rating and state estimation. Technologically it is similar to application #13 in that it involves the use of smart ICT technologies to improve management of an existing grid. Consistent with the assessment of smart meters and ICT for grid and outage management in Table 4 this case study was principally utility-funded, with some public assistance, but the technical, policy and economic aspects remain relevant to understanding application #3.

The primary driver of the application of advanced network management techniques in the Orkney Islands was the need to manage the variability of the abundant renewable energy sources within the operating constraints of the network, so as to avoid the cost of upgrading the network. Upon reaching a certain level of renewables penetration, further renewable installation would have required an additional subsea cable (with a cost of around £30 million) and internal island upgrades in order to 'accommodate' the potential generation output in a circumstance where the output is uncontrolled (Smarter Grid Solutions, n.d.). However, by monitoring the state of the network in real time and reducing distributed generation output when the grid is under stress, network management techniques could accommodate more renewable generation and minimise network augmentation costs.

The second case study covers five installations of batteries 'deep' within the distribution network by an American power utility to reduce expenditure on network upgrades. American Electric Power (AEP) pursued this approach because peak load on transformers or lines within the network could be reduced by charging the battery at off-peak times and discharging at times of higher load (also known as 'peak shaving'). This avoided the need for augmentation of existing grid components, which is similar to the application described as decentralised storage in Table 3 and Table 4. Again the case study projects were principally utility funded with public assistance, consistent with the assessment of decentralised storage in Table 4. Nevertheless the technical and economic aspects of using distributed storage to avoid network expenditure on augmentation of existing grid assets will assist with understanding application #3, which utilises storage to reduce expenditure on grid extension.

As well as peak shaving, these projects were also intended to improve the company's ability to meet reliability targets by supplying local customers in the event of an outage, while 'islanding' users while the network is under repair. Islanding involves electrically disconnecting part of the network so that it can continue to receive power from local sources irrespective of the status of the wider network, such as when the wider network is experiencing an outage. Collectively, peak shaving and islanding benefits represent a potential source of cost saving and service enhancement, respectively, for grid extensions augmented by distributed storage.

3.1.3 Conclusions from case studies

The Orkney Islands case evolved in response to a relatively specific set of circumstances. The combination of attractive local intermittent renewable resources, regulatory requirements to ensure grid connections could manage fluctuations in supply and demand, and the costly nature of augmenting the existing grid drove the use of active network management. Public funding and regulatory financial incentives were also present and important in driving the development and deployment of necessary elements of the overall solution.

Nevertheless, there will also be many cases where developing countries will have high quality renewable energy resources in areas that require grid extension. Solar resource will often be available and of high quality, whilst some locations may have viable wind generation sites. Importantly, these resources are intermittent and active network management approaches of the type developed in the Orkney case could allow greater use of local renewables whilst keeping network infrastructure within operational limits.

The United States peak-shaving examples also arose in response to a specific, but relatively common, set of network arrangements. At least three of the five US peak-shaving case studies were applied on radial feeder lines that were nearing capacity. The network arrangements of the other two projects were not specified in company documents but appear likely to also be located on radial feeders (Nourai & Kearns, 2010). A further peak-shaving/islanding case study was implemented by S&C Electric to improve reliability to the town of Field in British Columbia, Canada, which is served by a long radial feeder through rough terrain where treefalls are common and repair work is challenging and slow (S&C Electric Company, 2014). Applications of this type are well suited to this network arrangement as long radial feeders are subject to a high risk of long duration outages. In the context of grid extension in areas with relatively low density population and/or challenging topography, radially fed network arrangements would be expected and technically similar applications could be appropriate and offer similar benefits.

Most of the peak-shaving case studies have been completely utility funded, without public support. While the first AEP peak shaving project was reliant on public funding from the US Department of Energy's Sandia Laboratories to be deployed, the latter examples have been utility-funded. Projects have been successfully implemented in both vertically-integrated markets (West Virginia and Indiana) and deregulated markets (Texas and Ohio). While AEP presentations on these projects indicate that the cost of the deployed technologies remains high and it is challenging to capture the diverse range of benefits from these applications, ongoing reductions in battery costs and improving project economics could see widespread deployment where similar radial network arrangements exist.

Together, both active network management and distributed storage approaches represent a potentially viable supplement to grid extension. This conclusion is drawn with caution as the case studies examined here relate to enhancement of existing, rather than new, grid infrastructure. Nevertheless, the applications are analogous as they employ smart decentralised technologies in a way that is compatible with, and reduces the cost of, a larger more conventional grid.

Limited implementation to date suggests that short-term actions may be best led by developed world utilities and governments. While the key elements of these approaches are technically mature, high costs (in the case of distributed storage) or the need for bespoke engineering solutions (in the case of active network management) has resulted in relatively limited implementation to date. Given this it may be necessary for developed world utilities and governments to continue to drive the development experience with these technologies before expecting widespread adoption in the developing world to improve network efficiency.

Box 1. **Key lessons: grid extension augmented with smart technologies**

- No developing world examples identified, but some analogous applications in the developed world
- Examples are utility funded and sometimes required public assistance
- Widespread application in developing countries is possible in future as radial feeder lines are a common part of rural grid extension and intermittent renewable resources are generally abundant in developing countries requiring grid expansion
- Limited implementation to date suggests that short-term actions may be best led by developed world utilities and governments

3.2 Grid-connected mini-grids (Application #6)

3.2.1 Application overview

While a lack of grid connection is often a major problem in developing countries, connected customers can also face access issues due to poor grid reliability. Even large cities such as New Delhi and Lagos experience frequent and persistent brownouts and blackouts, and can suffer from poor power quality.

Unreliable and poor quality power supply affects a range of activities including households, small commercial businesses, manufacturing, public services and critical facilities such as hospitals.

A common response to poor power reliability and quality is the installation of generators, predominantly diesel fired, at the customer's premises. These generators are run whenever power is lost or degrades substantially in quality. While this solution is technologically simple and relatively reliable, it exposes the user to high and fluctuating fuel costs and harmful (both locally and globally) combustion emissions. Given the cost and pollution, not all users adopt this response, and instead go without power during disruptions to grid service.

An emerging response to poor grid reliability and power quality is the installation of a local, grid-connected 'mini-grid' that combines distributed generation, storage and smart control systems. These systems can provide a cost effective alternative to solely relying on diesel generators by displacing some diesel use with cheaper renewable generation sources, minimising diesel operation through battery storage of grid electricity and through improving the efficiency of diesel operation by allowing it to operate at more efficient load levels. Smart control systems can achieve enhanced system reliability by integrating renewable and fossil generation sources, managing the availability of battery or fossil energy, and 'islanding' users from the grid when faults or outages in the wider network are detected.

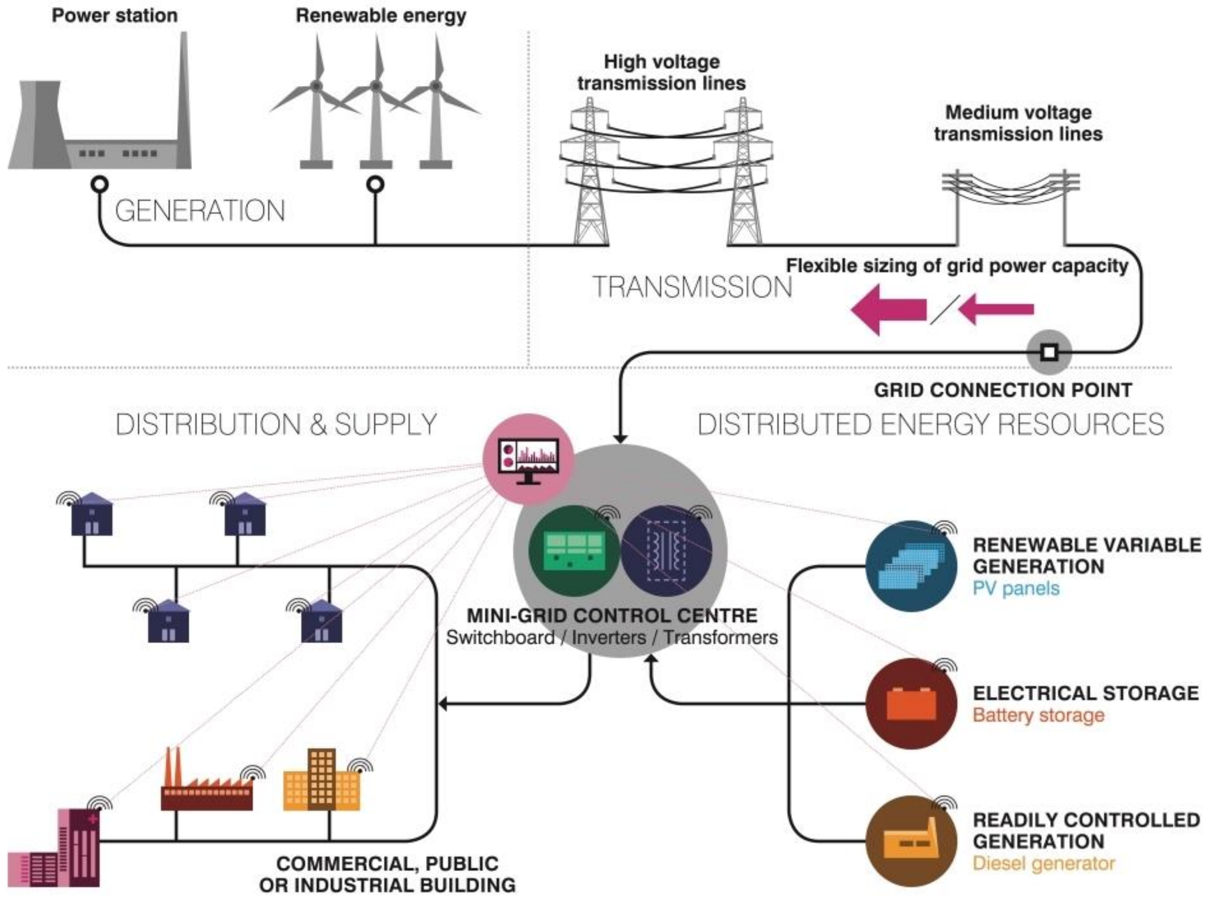
Typically a 'mini-grid' is defined as local generation, storage and network assets supplying more than one user through a system not controlled by an electric utility. For the purpose of this discussion, we define a grid-connected mini-grid slightly more broadly as any combination of non-utility controlled generation, storage and smart controls within a grid-connected system. In addition to the traditional conept of a mini-grid, this definition captures systems serving a single user.

The key benefits of a grid-connected mini-grid are enhanced reliability, particularly when compared to the reliability of the wider network, and reduced costs compared to a basic diesel generator back-up approach. Use of storage and smart controls to integrate local renewable resources can reduce fuel costs and support sustainable, low emissions energy production. A grid-connected mini-grid can also export excess power from distributed generation sources while managing generation output within the constraints of local user needs.

On the cost side, sophisticated mini-grid applications are typically more capital-intensive than a basic diesel generator approach, and also can have higher maintenance costs. Also, the process of obtaining necessary approvals to establish the system with the wider grid provider can be long and costly, depending on the location and approach.

The components of a grid-connected mini-grid are illustrated in a stylistic fashion in Figure 3.

Figure 3. **Stylised depiction of a grid connected mini-grid**



Source: Arup

3.2.2 Case study analysis

Two distinct types of case studies are investigated in respect of this application:

– two case studies where an anchor customer underpins the development of a grid-connected mini-grid; and
– five case studies involving single user 'mini-grids' that have adopted various combinations of fossil and renewable distributed generation, batteries and control systems to mitigate the effects of an unreliable grid connection.

The two sets of case studies are grouped due to their similarity. They are described briefly below, with further detail available in Appendix B.

The first anchor customer case study involves the use of biomass gasifier-based mini-grids in India installed by DESI Power between 1996 and 2012. The DESI Power business model depends upon the identification or development of an anchor customer to provide regular electricity demand, which can then underpin service to previously unserved residential customers. Anchor customers utilised to date are either agribusinesses or telecommunications towers. These high demand users are individually metered and charged on a per unit basis. They both generate the majority of revenue for the micro-grids and require relatively low expenditure on distribution and tariff collection.

The second case study involves construction of a new hydro power plant on the Mwenga River in Tanzania by Rift Valley Energy underpinned by demand from the nearby Mufundi tea and coffee factory. The factory acts as an anchor customer, underpinning the viability of the mini-grid and allowing the extension of electricity to a number of nearby communities. Hydro power is also exported to the national grid.

The five single user grid-connected mini-grid case studies cover a diverse range of end users and locations. Collectively the range of case studies highlights the potential for a range of relatively simple applications of distributed generation, battery storage and management systems to provide reliable power to users suffering from poor grid reliability. These case studies are summarised in Table 7.

Table 7. **Summary of single-user grid-connected mini-grid case studies**

Location	End user	Energy supply after upgrade	Uses of storage	Primary drivers
India (Tamil Nadu)	Cotton Mill	Grid power backed up by PV and diesel	None	Cost
Nigeria (Lagos)	ATMs	Grid power backed up by PV and batteries	Reliability	Cost, local emissions
Haiti (Cap-Haitien)	Hospital	Grid power backed up by PV, batteries and diesel	Reliability	Cost, reliability
India (various)	Telecommunications towers	Grid power backed up by batteries and diesel	Reliability, enhancing diesel efficiency	Cost, reliability
Nigeria (various)	Petrol stations	Grid power backed up by batteries and diesel	Reliability, enhancing diesel efficiency	Cost

Source: Vivid Economics and Arup

In each case the project was privately funded by an organisation with high commercial or operational needs for reliable power. In all cases the user had previously met that need through use of diesel generation, and the projects involved replacing or augmenting that diesel use with renewable generation and/or batteries. The systems use proven, commercially available technologies and generally demonstrate strong economics. However, despite the use of decentralised technologies that could potentially contribute to wider network efficiency, the applications do not appear to be designed or intended to achieve this.

3.2.3 Conclusions from case studies

The grid-connected mini-grid examples presented here demonstrate the potential advantages of mini-grid solutions in grid-connected areas in a range of contexts. Applications range from complex multi-user projects supplying both large commercial customers and small rural households, to small single-user projects for loads as small as an automated teller machine. Where the multi-user networks have both expanded electricity access to new users, the single user examples have sought to maintain or increase supply reliability in the face of an unreliable grid whilst reducing costs to acceptable levels.

A further common theme in the larger networks is the use of an anchor customer to expand supply to other smaller customers that would not be feasible to supply on their own. To achieve this, these networks need to be able to develop agreements with and appropriately bill different types of consumers. Difficulties with developing demand have prevented DESI Power from expanding beyond the relatively small number of mini-grids that they currently operate; the Mwenga hydro plant has benefited from the application of advanced metering infrastructure and new, streamlined small power producer regulations. By contrast, single user networks avoid these problems, but often need to deal with more variable load or generation. This requires strong and technically sophisticated systems for managing different elements of the network; automated systems are necessary as it will typically be infeasible to manage these elements manually.

The single user cases demonstrate that a diverse range of businesses are willing to employ their own capital to install storage, distributed renewable generation and management systems to displace existing fossil-based distributed generation; this suggests strong growth potential for similar applications. These systems would appear to be technically capable of matching or exceeding the reliability of the traditional diesel generator as back-up for an unreliable grid. The project economics of these approaches appear strong in a range of markets and for a range of businesses, generally sufficient to attract the end user’s own capital to fund the investment. These factors indicate potential for rapid, spontaneous and private-sector led growth of similar applications.

Given the potential for spontaneous, private sector-led growth in this area, the challenge for policy-makers, regulators and utilities is to capture the potential broader network efficiencies from this trend. Each of these projects create a new asset that could, under the right policy and economic settings, be made available to contribute to broader network efficiency. Storage assets can absorb power from the grid at times of grid availability and return it to improve the system balancing; similarly distributed diesel generators that are not operating at full capacity due to the output of renewable generation could be run at a higher capacity to export power when needed. However, none of these potential benefits for network efficiency appear likely to be captured in the applications analysed above. The assets are, understandably, designed to be operated solely for the user’s needs and to operate when islanded from the grid, but not to export to or otherwise stabilise the grid. Market and regulatory settings, and energy supply business models, do not appear well designed to capture potential broader benefits of this trend for network efficiency. Failure to do so could represent a lost opportunity; conversely well targeted interventions could potentially leverage a substantial volume of private capital to improve network efficiency. Interventions of this type are considered further in section 4.3.

Box 2. **Key lessons: grid-connected mini-grids**

- Given low and uncertain demand from households an ‘anchor customer’ approach is one viable approach to expanding grid access
- A range of single users are willing to pay for mini-grid systems based on storage and/or local generation to enhance reliability in the face of low quality grid service
- While these applications have the potential to enhance wider network efficiency, this potential does not seem to be widely captured and would appear to be a key area for greater policy focus

3.3 Grid-ready mini-grids (application #7)

3.3.1 Application overview

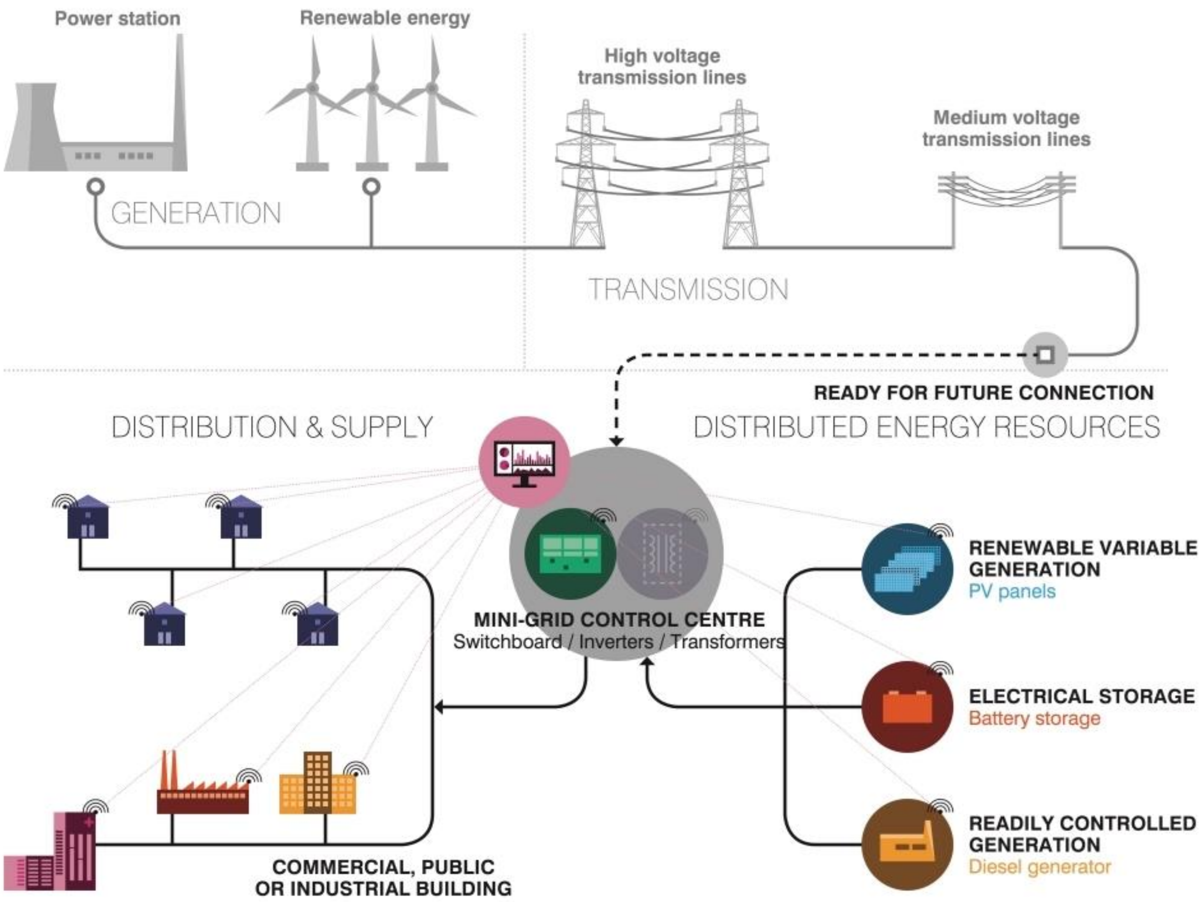
The installation of an off-grid mini-grid is often the most economically efficient way to bring power to communities which are remotely located or are unlikely to consume enough electricity to justify a grid extension. However, over time, electrical access from the mini-grid is likely to support economic development, increase incomes and electricity demand. As demand increases, the economic case for connection to the main grid may become justified.

The process of connecting a previously islanded mini-grid with the main grid raises a range of technical and commercial issues. A ‘grid-ready’ mini-grid is a mini-grid that has been designed and/or commercially arranged in a way that anticipates and facilitates this interconnection. Designing a mini-grid to be grid-ready is not costless. A mini-grid operator may need to install additional switchgear and metering at the point of likely interconnection, allow for additional capacity in switchgear and equipment, provide higher specification protection systems and higher equipment ratings, install additional control functions on generation units, install additional mini-grid ICT and control functions, and ensure higher quality construction and installation of components. The case for anticipating and incurring these costs upfront against doing so at the time of interconnection will depend on the difficulty of retro-fitting suitable equipment after the initial installation, as well as the expected time between commissioning and grid-connection; a key benefit of a grid-ready mini-grid is the avoidance of these retro-fitting costs.

The critical benefits of a grid-ready mini-grid are the stronger dynamic incentives created by understanding (both commercially and technically) how the grid will operate in the event of grid-connection. As stated above, off-grid mini-grids can support development objectives and a successful mini-grid may, in fact, accelerate the timetable by which grid connection is attractive by increasing incomes and electricity demand. However, the operator of a mini-grid may be concerned about their return on investment in the event of interconnection, which may complicate and even prevent the initial development. From this point of view, apart from the technical aspects of being grid-ready, it is critical that policy and regulatory processes provide clarity and certainty for such investments. Key elements of this include standardised power purchase agreements for distributed generators, and clear guidelines and procedures for interconnection.

The components of a grid-ready mini-grid are illustrated in a stylistic fashion in Figure 4.

Figure 4. **Stylised depiction of a grid-ready mini-grid**



Source: *Arup*

3.3.2 Case study analysis

The three grid-ready mini-grid case studies address a range of outcomes to illustrate the variation in outcomes that are possible. These case studies are:

- The Darewadi (India) case study is an example of a mini-grid that was explicitly designed to be grid-ready
- The Athureliya (Sri Lanka) case study gives an example of a mini-grid that was not initially designed to be grid-ready but where regulatory and commercial settings supported adaption of the mini-grid to connect with the main grid; and

– The Sagar Island (India) case study illustrates the effective abandonment of a mini-grid in the face of grid extension and inadequate incentive to promote ongoing utilisation of the mini-grid assets.

They are described briefly below, with further detail available in Appendix B.

A grid-ready mini-grid was installed by Gram Oorja in the Indian village of Darewadi village in the district of Pune. The village has a population around 220 people. It has no grid connection. With upfront costs covered by Bosch, Gram Oorja installed a solar powered mini-grid with a peak capacity of 10 kW to serve Darewadi. 40 local households were connected and billed on a per unit basis. Use is measured through individual meters, with the proceeds covering the cost of battery replacement and grid maintenance. The mini-grid was designed to be 'grid-ready' by following the wiring regulations of the Maharashtra's State Electricity Regulatory Board despite the higher initial cost of this approach. The design further supports quality of power supply and grid readiness through separating the network into three feeders: households, street lights and commercial loads.

In the case of the Athureliya village in Sri Lanka, electricity was provided through a small-scale hydro plant and mini-grid until 2010 when the village was connected to the national grid. After the national grid was extended to serve the village, utilisation of the hydro plant was initially limited to a small number of households that could not afford grid connection. However, the hydro plant was retrofitted in 2012 to allow it to export electricity to the grid, underpinning the ongoing economic operation of the plant and generation of revenue for the village.

Such a retrofit would have required investment, and therefore regulatory certainty is important. Sri Lanka's Sustainable Energy Authority has issued a guidebook laying out the steps for interconnection, which requires a pre-feasibility study, approval for developing a specific resource and the granting of an energy permit (Sri Lanka Sustainable Energy Authority, 2011). The Athureliya experience indicates that a streamlined process can clarify the commercial incentive to incur these retrofit costs and support timely retrofitting.

In contrast to the experience in Darewadi and Athureliya villages, the mini-grid infrastructure constructed on Sagar Island has been largely discarded as the grid has expanded. It therefore forms a negative example, demonstrating the potential costs incurred when mini-grids are not designed as 'grid-ready'. Almost all of the pre-existing mini-grid infrastructure has been discarded in the recent push to connect the island to the central grid. While it is unclear why the existing infrastructure is not being used, it is possible that the existing infrastructure is not functioning at a reasonable level; independent analysis of the programme conducted in 2008 questioned the sustainability of the management systems for the solar mini-grids, raising doubts as to whether they would be able to raise sufficient revenue for maintenance. The lack of clear regulation on interconnection, discussed in the Darewadi case study, may also play a role.

3.3.3 Conclusions from case studies

Each of the three above examples demonstrates the importance of building grid-readiness into mini-grids, especially within the context of countries where electricity access is rapidly expanding. Where clear regulation exists for managing interconnection, as in the Sri Lankan example, the costs of retrofitting can be assessed against the value of the mini-grid assets to support rational interconnection decisions.

A range of policy and regulatory points are important. Key steps to support grid readiness include clear interconnection guidelines and standards, standardised power purchase agreements to create clear financial incentives for generation assets to continue operating, and a simplified and well-structured interconnection procedure. These elements should facilitate either pre-emptive design decisions to be grid-ready, or timely retrofitting actions to allow mini-grid assets to operate viably after interconnection.

The Sri Lankan case study illustrates that, while streamlining interconnection processes do not reduce the infrastructure costs of interconnection, they do provide new build mini-grids with a roadmap to facilitate eventual grid connection. They also gives investors in mini-grids and generation assets greater long-term security, ensuring that in the event of grid extension their assets can still be profitably operated, rather than being displaced by (subsidised) grid electricity. In cases such as Sri Lanka where a large number of mini-grids are already in operation, the technical aspects of grid connection, such as synchronisation, will have to be retrofitted at the time of connection. However, the Athureliya experience indicates how a streamlined process can clarify the commercial incentive to incur these retrofit costs and support timely retrofitting.

The technical solutions which can aid the development of a grid-ready mini-grid are a mixture of common sense, good design practices and some advanced technologies. Critical steps for a mini-grid developer to follow are:

- following local and recognised international electrical engineering standards, such as the IEEE 1547 wiring regulations;
- planning, design, operation and maintenance of a safe electrical system through installation of appropriate breakers and/or fuses to reduce risk of overload and indirect contacts, and appropriate cable choice and installation for dwelling type and environmental conditions;
- specifying switchgear, cables, and other equipment up to the standards for the primary grid;
- specifying flexible controls (for example, islanded mode, grid-connection mode, synchronisation mode, etc.) for mini-grid generation units and the master controller;
- allowing for future growth in capacity through cabling, transformers and higher fault current ratings, noting that this may entail higher upfront costs; and
- providing additional space in switchboards and switchrooms.

For utilities that may need to connect to mini-grids in future, advanced multi-function relays can simplify the interconnection procedure and reduce upgrades costs by facilitating the reconfiguration of the protection system.

In general, commercial, regulatory and technical aspects of grid-readiness are important as a lack of clarity in the effect of interconnection on investors in a mini-grid could potentially deter investment in mini-grids, harming the achievement of electricity access goals.

Box 3. **Key lessons: grid-ready mini-grids**

- Commercial, regulatory and technical aspects of grid-readiness are important to underpin investments in mini-grids
- Standardised power purchase agreements and clear interconnection guidelines are key commercial and regulatory aspects of grid-readiness
- Numerous technical steps can be undertaken to ensure grid-readiness, including specifying equipment standards to the level of the primary grid and flexible controls for mini-grid generation units

3.4 Smart metering and ICT to address non-technical losses (application #12)

3.4.1 Application overview

In electricity supply, losses refer to the amount of electricity injected into the transmission and distribution grids that is not paid for by users and have two components: technical and non-technical. Technical losses consist mainly of power dissipation in the electricity system components. Non-technical losses consist primarily of electricity theft, non-payment by customers and errors in account and record-keeping.

Non-technical losses represent a potentially avoidable financial loss for the utility, and can have significant wider effects on the availability and price of electricity in the wider community. Lost revenue from non-technical losses either have to be absorbed by supply companies, with potential consequences for the quality of supply, or be paid for as an implicit cross-subsidy by other consumers.

There are several common causes of non-technical losses. These include illegal connections to the grid, typically to the low voltage network; tampering of a consumption meter; unmetered or inaccurately metered consumption; and bribery or intimidation of utility employees to avoid metering of or payment for electricity.

Smart metering coupled with effective communication systems via ICT networks can address all the types of non-technical losses listed above. Smart remotely-read meters can allow customers to be directly metered from the point of connection to the medium voltage network, meaning that if theft occurs from the low voltage network it occurs ‘behind’ the meter and therefore is at the expense of the customer rather than the wider network. Remotely-read meters can also be located in secure boxes rather than on the customer’s premises, reducing the risk of tampering. Further, remote communication of meter data with high quality metering and communication equipment reduces the risk of inadvertent inaccurate billing and complicates any attempts by employees of the utility to collude with customers to reduce billed volumes. In combination with the steps described above, ‘master’ meters located within the distribution network can be used to record flows to separate parts of the network, assisting to monitor flows and losses, including non-technical losses across a wide area and focus attention on where losses are occurring.

Smart metering and remote communications must often be combined with wider changes to the distribution network to effectively combat non-technical losses. Principally these involve increased use of medium voltage distribution lines at the expense of low voltage lines, placement of low voltage lines that increases the difficulty of illegal connection, and use of secure pole top infrastructure for switching and metering.

The measures described above imply significant upfront costs associated with re-engineering of distribution networks, installations of new metering and communications infrastructure, and system design. While operating costs can also be reduced by avoiding manual meter reading, the primary benefit of these measures is in increasing billing volumes and therefore revenues.

3.4.2 Case study analysis

This application is investigated through three case studies where distribution companies employed smart metering technology and broader network re-engineering to combat power theft. These case studies are Ampla in Rio de Janeiro, Brazil; Tata Power Delhi Distribution in Delhi, India; and Edesur in Santo Domingo, Dominican Republic.

The core of Ampla's approach was to build a distribution network where medium voltage and low voltage are located on the same pole and each individual customer was directly connected from a medium to low voltage pole mounted transformer. Smart meters were located in secure boxes at the top of distribution poles rather than at the customer premises, reducing the risk of meter tampering. Each customer was connected to the meter box by a dedicated circuit, which itself was directly connected to the medium voltage network to reduce opportunities for theft from the low voltage network. The meters communicated consumption data remotely to the utility, allowing billing and consumption data to be handled via mobile phones or in home displays. As well as reducing operating costs, this approach reduced safety risks to billing staff entering slum areas. Further, by locating meters on the top of electricity poles at the point of connection to the medium-voltage network, theft from the low voltage wires would be 'behind' the meter and so be at the expense of the customer rather than the wider network.

Ampla's introduction of smart meters indicates both that these approaches can be technically effective, but also that they can generate social backlash. In 2003, Ampla reported non-technical losses for some parts of their concession area exceeding 50 per cent. Losses of this magnitude drastically impair the ability of the utility to make any return on an investment in improved supply. Ampla had losses of 23 to 25 per cent for Rio de Janeiro as a whole. Bills for many households increased significantly and, in some cases, unexpectedly. There were many cases of legal action against Ampla; at its peak, there were 447 lawsuits and court processes linked with the smart meters during one month in 2007 (Carvalho, Germini, van den Berg, & van Tuijl, 2014). Tensions emerged between the company and local politicians.

Ampla have dealt with the backlash through implementing a broad set of social development initiatives (Carvalho et al., 2014). These include:

- education campaigns to encourage more efficient energy use;
- replacement of old appliances with more efficient alternatives;
- recycling programmes, with consumers offered rebates on their bills in exchange for materials;
- capacity building on energy consumption for professors and students at public schools; and
- capacity building for young adults finding their first job.

In contrast to the Ampla case, the Tata Power case in Delhi saw smart metering deployed primarily to tackle electricity theft by high volume consumers. Most of these users were industrial or commercial, who relied on collusion with meter reading staff to reduce electricity bills. Jointly, consumers with a demand greater than 15 kilowatts represented only three per cent of total users but contributed almost 60 per cent of revenue. The Tata Power case suggests that focusing on high volume users offers good value for money given the relatively high cost of smart meters. Further, it may minimise the potential for social backlash. Again in contrast to the Ampla case study there is little evidence of significant legal or political action against Tata Power following the introduction of smart metering.

Tata Power's drive to reduce non-technical losses was extended to high income residential consumers and, finally, low income residential consumers. However, smart metering formed a smaller component of the overall strategy as it was extended to lower volume users. Technical measures were combined with community programmes to increase billing transparency, improve awareness of the dangers of illegal wire-tapping and increase availability of support for households. As in the Ampla example, small customer theft was also addressed by redesigning the low voltage distribution network to increase the difficulty of tapping wires. Principally this involved replacing low voltage distribution lines with medium voltage lines. Small transformers were positioned near load sites to step down the voltage at the point of connection for each consumers. Where low voltage lines were exposed, the traditional bare cables were replaced with insulated aerial-bunched cables which are better protected from theft as well as weather related damage.

In the Dominican Republic case study, advanced metering infrastructure was used to target non-technical losses from a range of customers, but with a strong focus on industrial customers. The scheme reached 7,400 large industrial and commercial premises and 18,100 low voltage customers. This was a key part of a broader electricity sector package supported by a World Bank loan, Total investment on the Advanced Metering Infrastructure (AMI) component was US$7.2 million.

As in North Delhi, advanced metering infrastructure was targeted initially at high volume industrial and commercial consumers. The installation of advanced metering infrastructure initially reduced losses and improved cash recovery; non-technical losses declined quickly from 38 per cent in 2005 to 32 per cent by 2008. However, these numbers are likely to overstate the effect of the smart meters themselves as other measures were introduced in parallel. Electricity theft was also made illegal in August 2007, with stringent penalties imposed on thieves, and the government was required to remain current on its electricity bills. Further there is some evidence that the programme underperformed in several key technical dimensions, including in appropriate data management and telemetry.

While the Edesur example faced difficulties, this does not suggest that the core technical approach was ill-suited; political will is also important to support such a programme. It is also difficult to isolate the failures of the advanced metering infrastructure programme independently of the performance of Edesur and policy-makers in relation to the broader World Bank programme, which was rated by the bank as 'unsatisfactory'. Particular blame was laid on the lack of political will to update retail tariffs to be cost-reflective or adopt tariff structures that automatically adjusted with exchange rates, the price of oil and inflation.

3.4.3 Conclusions from case studies

Jointly, these three case studies illustrate the potential advantages of advanced metering infrastructure. Remote meter reading, in particular, can clearly form an important element of a theft reduction strategy by allowing the placement of meters in difficult to access, tamper-proof boxes, by ensuring that the only low voltage parts of the network are 'behind' the customer meter, and removing the incentive for meter readers to collude with large energy consumers. Targeting high quantity users may be particularly cost effective – enabling much greater cash recovery at relatively low expense and with less risk of social backlash.

However, isolating the effect of smart meters within any of the case studies above is not possible. In each case, advanced metering was implemented alongside a much broader program to reduce theft, including social programmes, legislative changes and institutional reorganisation. In the cases of Ampla and Edesur the use of advanced metering complemented comprehensive redesign of the distribution network to reduce the risk of theft.

The examples of Ampla and Edesur also demonstrate the importance of both wider enabling reforms and a conducive environment. In the Ampla case, the early technical successes of the programme were threatened by social and political backlash, and enabling reforms were necessary to sustain its ongoing expansion. In the case of Edesur poor management appears to have led to technical difficulties and undermined the broader electricity turn-around strategy, stalling the programme despite the economic incentives generated by the staged World Bank funding.

The challenges to the Ampla and Edesur programmes contrasts with that in North Delhi. Tata Power was provided with strong incentives to reduce non-technical losses, and demonstrated sufficient technical expertise and political will to deliver a sustained and successful programme. The regulator set targets each year for technical and non-technical losses, with the target decreasing to reflect improvements in distribution and billing. Tata Power is allowed to keep revenues from electricity that is billed over and above the target set for the year. By consistently outperforming the target, Tata Power has increased annual profits. This ensures that the distributor has a positive incentive to decrease non-technical losses, and that the institutional incentives are aligned with the broader interests of the electricity sector.

In essence, the technological approach to reducing non-technical losses must be implemented in coordination with efforts to overcome social and political barriers. For instance, there is evidence in some contexts of a strong correlation between electricity theft and electoral cycles, with greater theft occurring nearer to polling dates (Min & Golden, 2014). This indicates the importance of understanding the broader institutional factors that result in high theft; the problem is not purely technical. As such, the evidence supports the potential for cost-effectiveness within the correct context. The key factors that have contributed to successful implementation appear to have been:

– execution in combination with broader social programmes to support theft reduction;
– strong incentive structures to encourage reductions in losses among distributors;
– local political will to reduce non-technical losses; and
– sufficient technical capacity among distributors to utilise data management systems to identify theft.

Box 4. **Key lessons: addressing non-technical losses**

– Targeting high quantity commercial users can be an effective first step in reducing non-technical losses
– Metering and network design elements of a solution can play a critical role
– Incentive structures can support desire to tackle non-technical losses
– Political will and technical capacity are also highly important
– Enabling social reforms such as energy efficiency, education and capacity building measures can improve the social acceptability of anti-power theft programmes, especially for low-quantity users.

4 Next steps

4.1 Introduction

Each of the priority applications identified has the potential to improve network efficiency in developing countries and there are likely to be untapped opportunities to employ them. There is a potential role for funds, such as the ICF, and donor organisations, such as DFID, in supporting their further development, and thereby improving electricity access and reducing emissions. This section seeks to answer two interconnected questions:

— Which countries are most likely to benefit from the applications identified?
— In what ways can donor action support understanding and utilisation of each application to support network efficiency?

Section 4.2 uses some basic quantitative analysis to determine which ICF priority countries could stand to benefit most from each of the applications. The analysis is necessarily high-level and constrained by data availability across countries. There will also be many aspects of DFID's relationship with individual countries that are hard to capture from an external perspective. The analysis should, however, provide a starting point for engagement with country offices.

Section 4.3 then considers potential actions that could support understanding and utilisation of each priority application. This is useful for planning potential outlets for ICF funding in two separate ways. First, projects could be structured to specifically address knowledge gaps, contributing to understanding of network efficiency interventions. Second, technical assistance projects could support trial deployments of an application, to build 'on the ground' knowledge and potentially support future privately financed deployment.

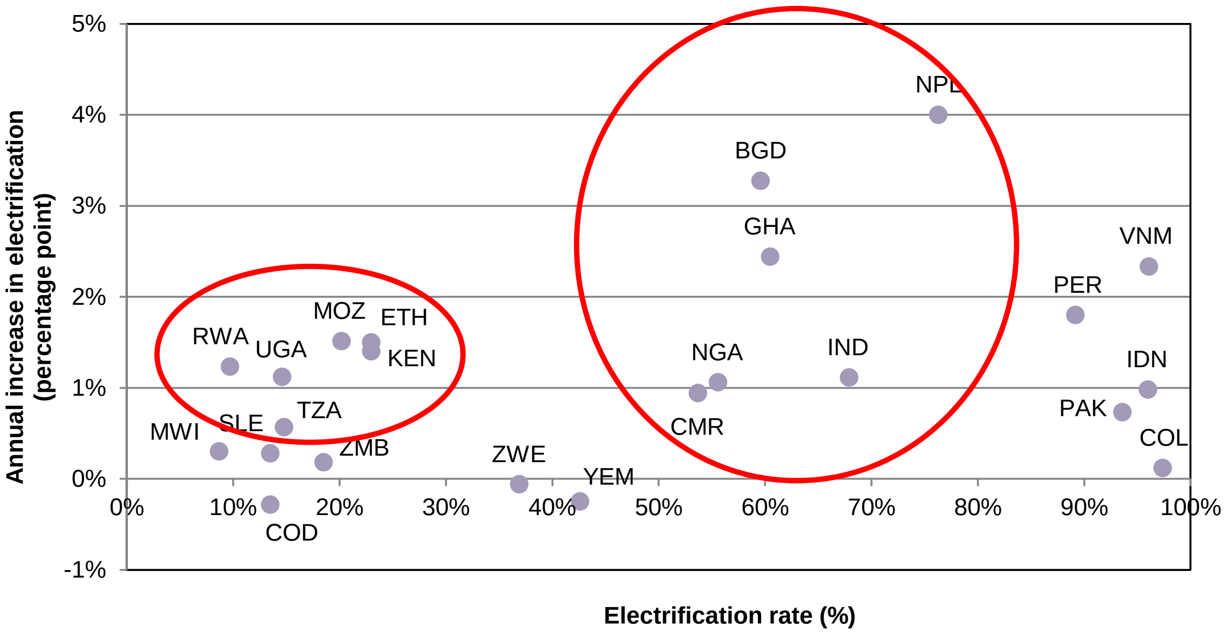
In combination, the answers to both questions sketches out a broad set of next steps that could be pursued using ICF or other donor funds to further knowledge and practice on networks in development.

4.2 Which countries are most likely to benefit from the applications identified?

4.2.1 Grid extension augmented with smart technologies

The use of smart technologies to reduce the cost of grid extension is most relevant in countries with rapidly increasing electricity access and low existing levels of electrification. Countries with these characteristics are likely to be investing a greater share of national resources into expanding the grid, and therefore can save more resources by intelligently managing distributed generation and storage to reduce the required capacity of network assets such as cables and transformers. Figure 5 uses data on both electrification rates and changes in electrification to identify groups of ICF priority countries that could fit this description. Unfortunately, data is only available for 22 of the 34 ICF priority countries, but there are still two separate groups that stand out as likely to benefit from partnerships in this area.

Figure 5. **Relationship between proportion of households without electricity and annual increase in electrification among ICF priority countries**

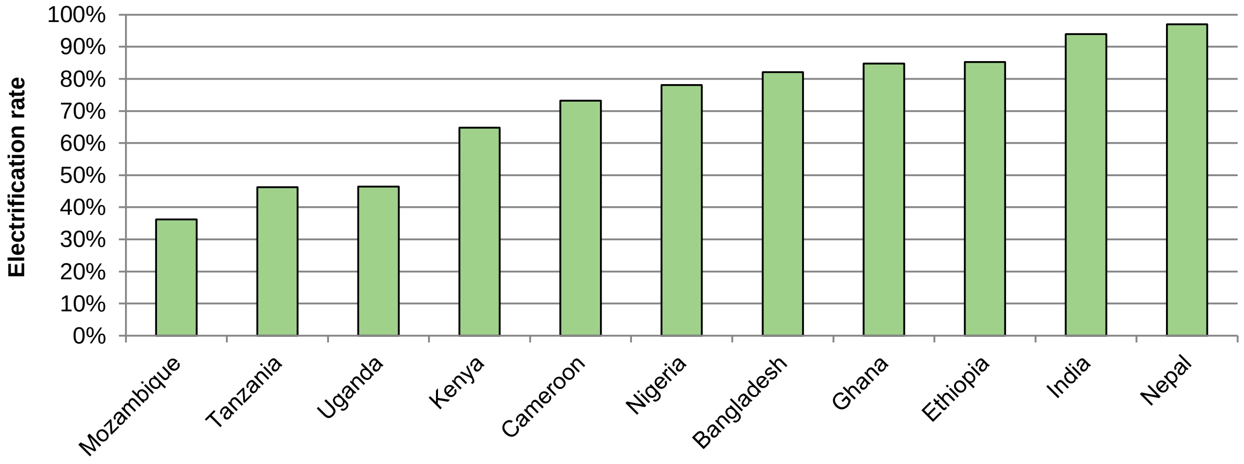


Note: *Annual increase in electrification is measured between the two most recent USAID Demographic and Health Surveys.*

Source: *USAID Demographic and Health Surveys*

Grid extension may not be applicable in all circumstances; in particularly remote locations a mini-grid directly using smart technologies may be a lower cost option in the short-, medium- and even long-term. Conversely, grid extension is highly likely to be the preferred electrification approach for unconnected urban or peri-urban consumers. This indicates that the most prospective locations for this application will have either or both of low urban electrification rates and high urban population growth rates, indicating potential for growth in urban and peri-urban connections. Figure 6 examines urban electrification rates for the countries highlighted above, while Figure 7 illustrates urban population growth rates. Together these charts indicate that all identified countries have urban population growth rates of at least two per cent, and therefore some potential for future urban grid extension.

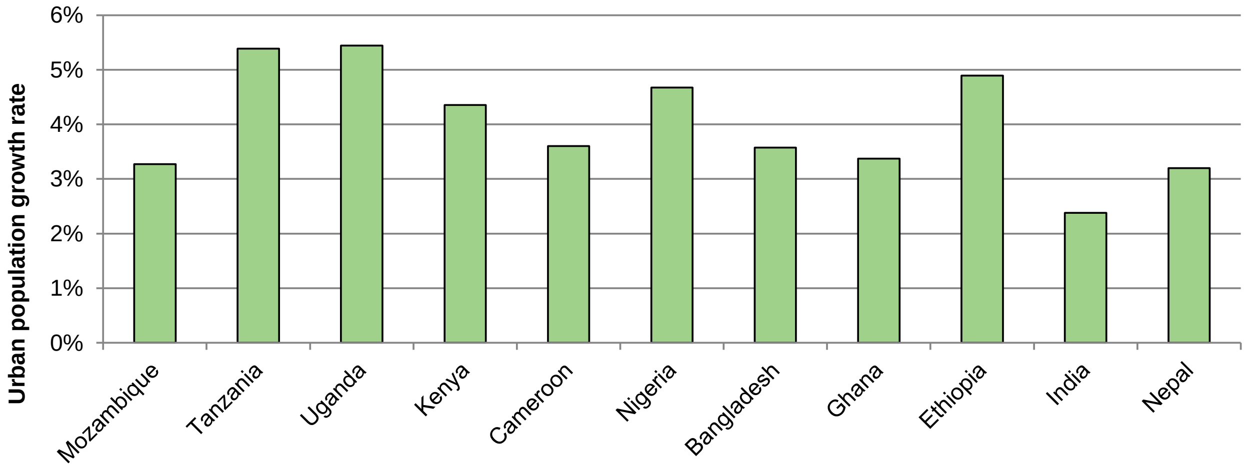
Figure 6. **Urban electrification rates for selected ICF priority countries**



Note: Rwanda's electrification rate was not available, but is assumed to be low

Source: IEA, World Energy Outlook

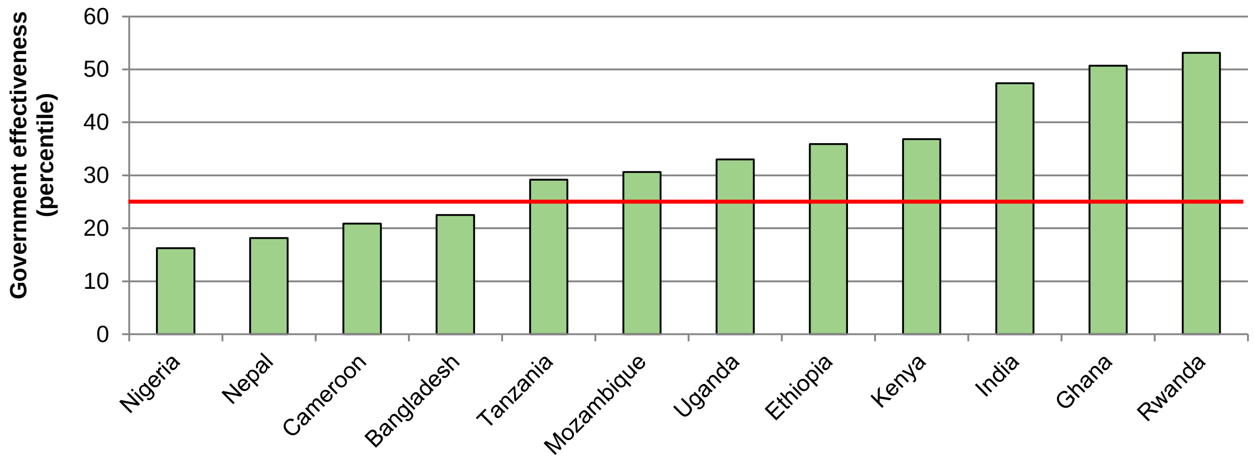
Figure 7. **Urban population growth rates for selected ICF priority countries**



Source: World Development Indicators

Grid extension augmented with smart technologies also requires significant technical capacity. Figure 8 indicates that Cameroon, Nigeria, Bangladesh, and Nepal are in the lowest quartile of government effectiveness of the 2015 countries examined by the World Bank. While utility technical capacity is not necessarily strongly correlated with broader government effectiveness, it appears likely that the technical capacity for grid extensions of this type may not be present in these countries. Conversely, Mozambique, Tanzania, Uganda, Kenya, Ghana, Ethiopia and India have stronger government effectiveness rankings and are more prospective locations for applications of this type.

Figure 8. **Government effectiveness metrics provide a proxy for technical capacity**



Note: *Score represents percentile rank of country among the 215 economies within the data set. Countries below the red line are in the lowest quartile of government effectiveness*

Source: *World Bank Governance Indicators*

Countries with high levels of unconnected urban residents and/or strong urban population growth, as well as sufficient levels of technical capacity to underpin 'smart' extension of existing grid infrastructure, are listed in Box 5.

Box 5. **Prospective countries for grid extension augmented with smart technologies**

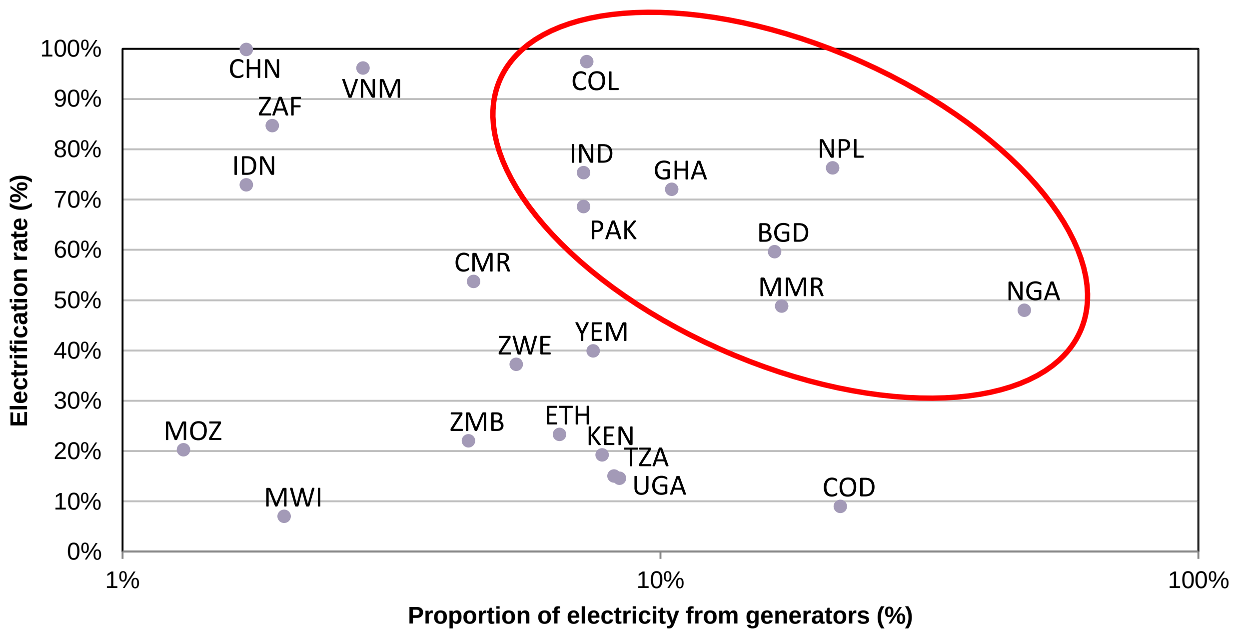
Rwanda, Tanzania, Mozambique, Uganda, Ethiopia, Kenya, India, Ghana

4.2.2 Grid connected mini-grids

In each of the case studies for grid connected mini-grids discussed above, the addition of generation or storage is used to supplement poor service levels from the national grid. The national grid is generally available but liable to suffer from blackouts or brownouts. Each case study included either an anchor consumer, with high demand for reliability, who effectively underwrote the installation of generation and storage to supplement grid service levels, or a single user demanding high reliability on its own behalf. The case studies illustrated recent moves for users with high reliability needs away from sole use of diesel generation to meet their reliability needs, towards more sophisticated mini-grid approaches combining renewable generation, storage and control systems.

This suggests that the potential for adoption of emerging grid-connected mini-grid approaches are highest for countries where the grid is widespread but unreliable. Figure 9 uses data from the World Bank to identify which ICF priority countries demonstrate both high rates of grid connection and high demand for improved reliability. Demand for reliability is proxied through the proportion of electricity consumed by firms that is generated via their own generator sets which, to aid exposition, is reported on a log scale. This approach is appropriate as use of on-site generators, generally diesel-fired, is presently the most common response of users that require high reliability and are willing to pay to achieve this reliability.

Figure 9. **Electrification rate versus proportion of electricity used by firms provided through generators**



Note: *Proportion of electricity from generators is measured by survey of firms in each country, with the surveys occurring between 2007 and 2014.*

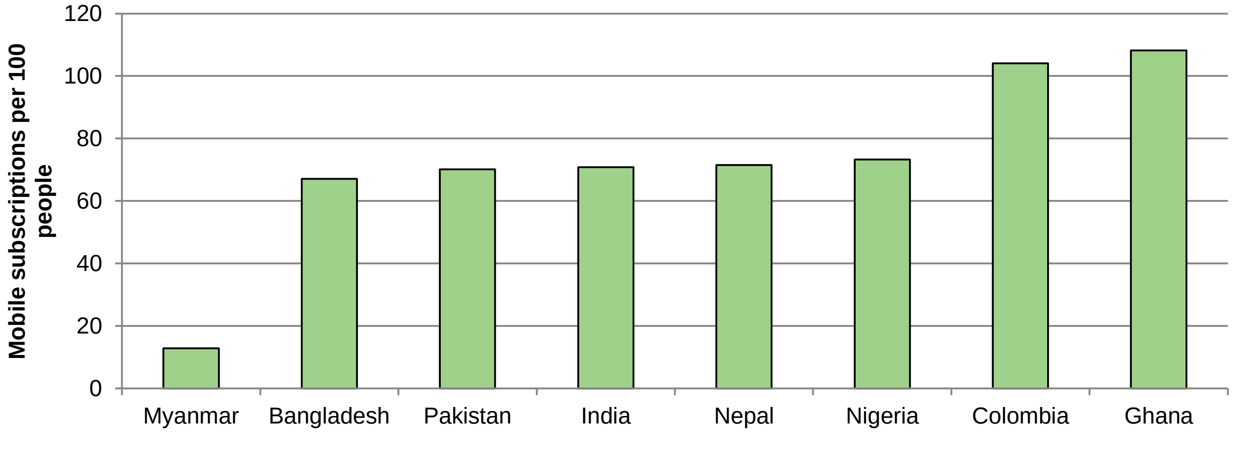
Source: *World Development Indicators, World Bank Enterprise Surveys*

A few countries stand out as particularly promising for further work on grid-connected mini-grids. Nigeria, Nepal, Ghana, Bangladesh, Colombia, Myanmar, India and Pakistan are highlighted within the red circle. Note that as the horizontal axis is logarithmic, it can be easy to underestimate the extent to which some countries are extreme outliers. For instance, the average firm in Nigeria reports that 48 per cent of the electricity it uses is provided through generators. This is more than double the 21 per cent reported in Nepal, and suggests that there is significant private capital that could be leveraged into mini-grid applications.

Despite the diversity of electricity users underpinning grid-connected mini-grid development seen in the case studies, a particularly large prospective group of energy users with high demand for reliability are telecommunications towers. The primary reason is scale; estimates indicate that the number of telecommunications towers in sub-Saharan Africa with a weak grid connection will expand from 84,000 currently to over 100,000 by 2020 (GSMA, 2014). Similarly analysis by the Indian Institute of Technology indicates that of the over 400,000 cellular base stations in India, over 70 per cent can only access grid power for fewer than eight hours per day (Jhunjhunwala, Ramamurthi, Narayanamurthy, Rangarajan, & Raj, n.d.). Another substantial advantage is that they tend to be widely dispersed across even very remote rural locations; this, combined with their need for significant volumes of highly reliable electricity makes them ideal anchor customers to underpin new off-grid or fringe-of-grid mini-grids. This is reflected in investment programmes targeting this approach undertaken by GSMA through its Green Power for Mobile programme (with support from organisations including DFID and the International Finance Corporation), and the Rockefeller Foundation through its Smart Power for Environmentally-sound Economic Development (SPEED) programme.

Mobile subscription rates can proxy the potential of telecommunications towers to support electricity access through the anchor customer approach or reliability using their mini-grid storage and generation assets. Accordingly, Figure 10 presents the mobile subscription rates for each of the eight countries identified in the red circle in Figure 9. Colombia and Ghana appear to have particular potential. Both have extremely high mobile subscription rates, with more than one subscription per person. In both countries telecommunications towers are likely to be widespread and might form effective anchor consumers for storage or generation systems to supplement the national grid. In Colombia electrification rates are high, but a significant proportion of electricity is delivered from diesel generators; this indicates that telecommunications could underpin grid-connected mini-grid approaches to improve reliability for both the tower and, potentially, nearby communities. In Ghana electrification rates are lower suggesting that both off-grid and grid-connected approaches could be viable.

Figure 10. **Mobile subscriptions for countries with high electrification and demand for reliability**



Source: *World Development Indicators*

The combination of countries with high electrification rates, widespread reliability issues, a willingness to pay to achieve higher reliability, and a likely substantial market of telecommunications towers to underpin grid-connected mini-grid approaches is set out in Box 6.

Box 6. **Prospective countries for grid-connected mini-grids**

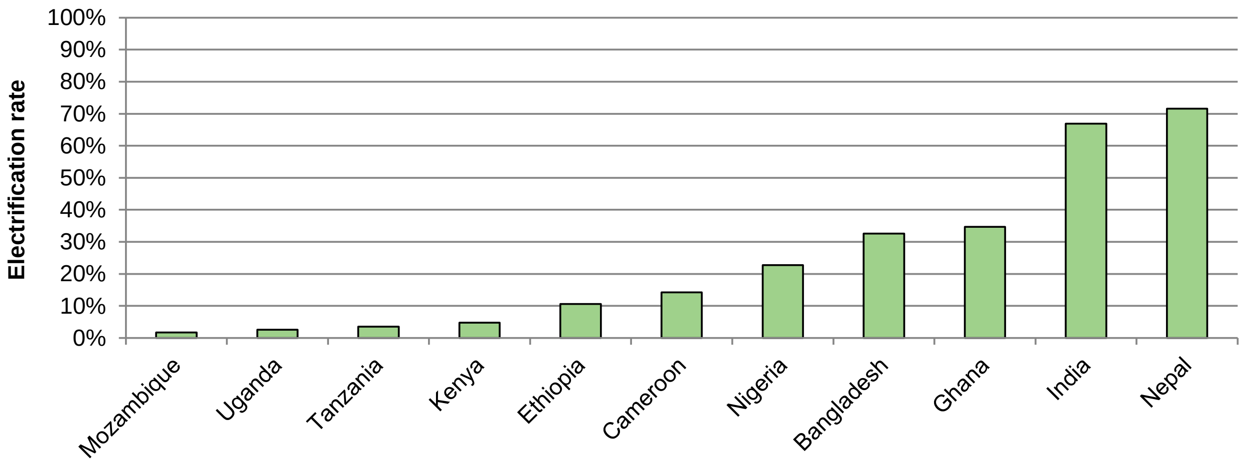
Ghana, Colombia, Nigeria, Nepal, India, Pakistan, Bangladesh

4.2.3 Grid-ready mini-grids

Grid-ready mini-grids are most relevant in countries with rapidly increasing electricity access and low existing levels of rural electrification. This is because mini-grids are more likely to improve rural electrification, so low rates of rural electrification indicate a strong need for mini-grids, and therefore a larger benefit from reducing their costs. Being 'grid ready' reduces the cost of a mini-grid by future-proofing infrastructure, increasing its useful lifespan and lifetime utilisation.

Accordingly the countries identified in Figure 5 as having relatively rapid growth in electrification that also have low rates of rural electrification are likely be most benefitted by making future mini-grids 'grid ready'. Figure 11 presents rural electrification rates across a range of ICF priority countries with relatively rapid growth in electrification. The entire Sub-Saharan African country sub-set, plus Bangladesh, has rural electrification rates below 40 per cent, indicating substantial potential for future growth.

Figure 11. **Rural electrification rates for selected ICF priority countries**



Note: Rwanda's electrification rate was not available, but is assumed to be low

Source: IEA, World Energy Outlook

Of the remaining countries, some are already making regulatory strides to support the integration of mini-grid networks into the national grid. One of the Working Groups of the India Smart Grid Forum, for instance, has been tasked with developing a 'set of standards, guidelines and technology recommendations' for integrating renewables-based micro-grids with the central grid. However, the findings of this working group have yet to be released externally, and the other countries highlighted seem to have taken no action specifically aimed at streamlining interconnection for small producers. Tanzania and Kenya are notable for already having regulation on mini-grid interconnection. Table 8 lists some of the leading policies for connecting small power generators among developing countries; generator connection agreements are an important part of the regulatory framework for interconnection of a mini-grid.

Table 8. **Leading regulation on interconnection of mini-grids and small renewables producers within developing countries**

Country	Responsible agency	Policy document	Year adopted	Generating capacity limit
Thailand	Energy Regulatory Commission	Regulations for the Purchase of Power from Very Small Power Producers	2002	10MW
Tanzania	Energy and Water Utilities Regulatory Authority	Guidelines for Development of Small Power Projects	2009	10MW
India	Renewables and Micro-grid Working Group of the India Smart Grid Forum	Interconnection standards and policy and regulatory aspects of micro-grids for India	In progress	To be determined
Kenya	Energy Regulatory Commission	Connection Guidelines for Small-Scale Renewables	2012	10MW
Sri Lanka	Sustainable Energy Authority	A Guide to the Project Approval Process for On-Grid Renewable Energy Development	2011	10MW

Note: *Based on Lawrence Berkeley National Laboratory, updated to reflect release of connection guidelines in Kenya.*

Source: *Lawrence Berkeley National Laboratory* (Greacen, Engel, & Quetchenbach, 2013)

This analysis highlights a range of potential partners for these interventions who have very low electrification rates, moderate recent increases in access to electricity and potentially underdeveloped regulatory arrangements for interconnection. These countries include Tanzania, Rwanda, Ethiopia and Kenya. Overall, this analysis suggests a diverse mix of countries where further work in this area may beneficial. These are listed in Box 7.

Box 7. **Prospective countries for grid-ready mini-grids**

Rwanda, Mozambique, Uganda, Ethiopia, Cameroon, Nigeria, Bangladesh, Ghana

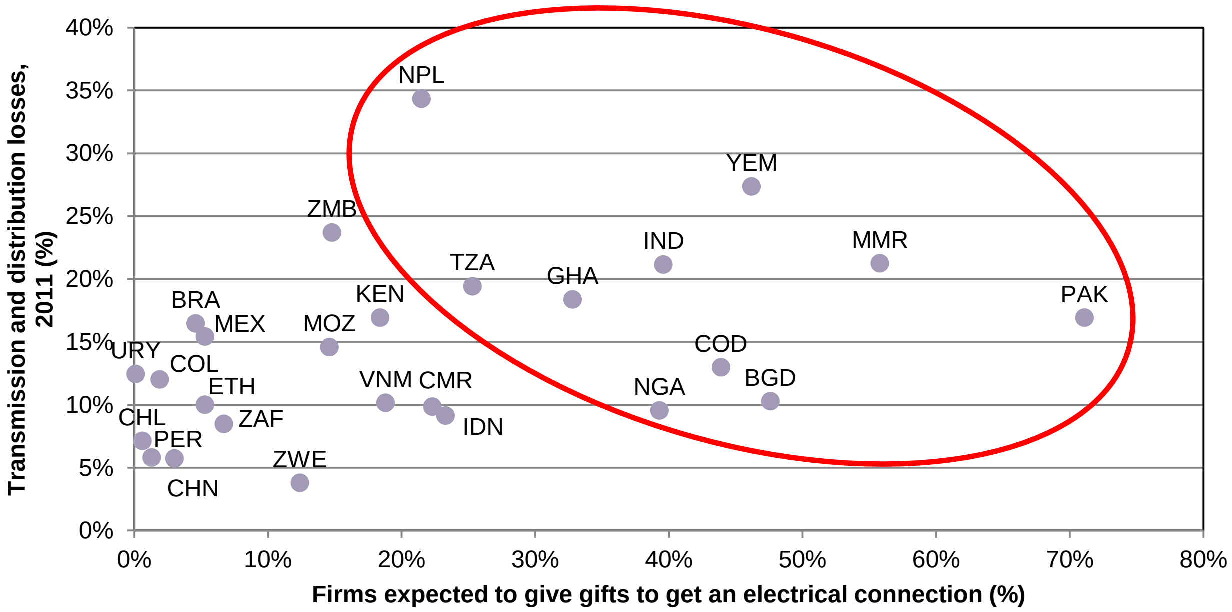
4.2.4 Smart meters and ICT to reduce non-technical losses

Unfortunately, it can be difficult to determine which countries suffer from large non-technical losses. There is no high quality, comparable data set with international coverage. Instead, information about non-technical losses tends to be collected piecemeal, with different methodologies applied by different countries and with some countries systematically understating the extent of electricity theft.

Figure 12 provides a broad approximation by plotting the total electrical losses for each country (combining technical and non-technical) against an indicator for corruption. Countries that both have extremely high losses and significant corruption within the electricity sector are likely to also suffer from high non-technical losses, though this may not always be the case.

Nepal, Tanzania, Ghana, India, Yemen, Myanmar, Bangladesh and Pakistan all stand out. Corruption in the electricity sector appears to be particularly widespread in several of the Asian countries considered, with over 70 per cent of firms in Pakistan reporting that they were expected to give gifts to receive an electricity connection. This metric was also above 40 per cent in India, Bangladesh and Myanmar. These countries also have among the highest losses; Nepal is the clear outlier at 35 per cent of generated electricity lost, but Yemen, Zimbabwe, India and Myanmar are all also above 20 per cent.

Figure 12. **Relationship between transmission and distribution losses and corruption in the electricity sector among ICF priority countries**



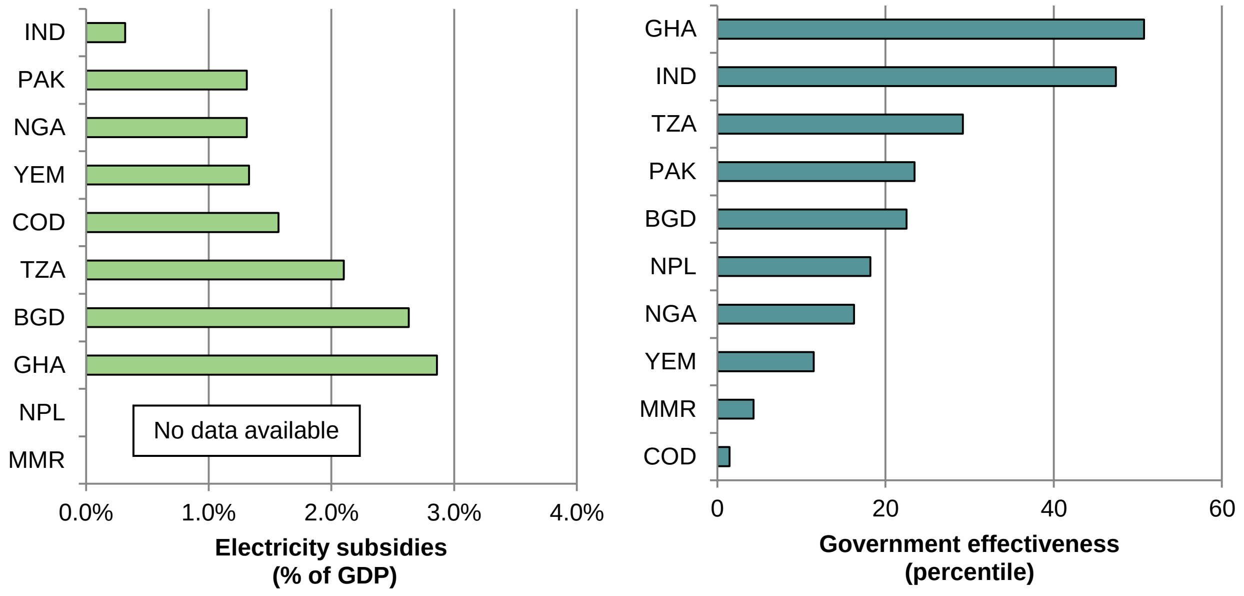
Note: *Percentage by survey of firms in each country, with the surveys occurring between 2007 and 2014.*

Source: *World Development Indicators, World Bank Enterprise Surveys*

For advanced metering infrastructure to be effective in curbing non-technical losses requires at least two additional factors to hold. First, the political will must exist to charge consumers more for electricity. Electricity theft can function as an implicit subsidy and politicians may be unwilling to cut it back. Second, the utility or distributor must have sufficient capacity to deliver the smart metering programme. Regardless of the level of technical assistance provided, reforming metering and billing systems is a complex task that will need to be largely executed by the local distributor, and is unlikely to function well if they do not retain the relevant skills or expertise.

A possible proxy measure for political will to reduce non-technical losses is the degree of electricity subsidy; high subsidies indicate political difficulties with charging for electricity. Figure 13 shows electricity subsidy levels for each of the countries identified above. Electricity subsidies are exceptionally high in Ghana, Bangladesh and Tanzania, suggesting that more fundamental factors may prevent effective smart meter programmes from reducing losses in these countries. However, subsidies are relatively low in India and Pakistan, at 0.3 and 1.3 per cent of GDP respectively. These countries may form strong potential targets for AMI programmes.

Figure 13. **Subsidy levels and government effectiveness for countries with high losses**



Note: *Score represents percentile rank of country among the 215 economies within the data set.*

Source: *World Bank Governance Indicators, IMF*

Figure 13 also shows government effectiveness across the same range of countries, as measured by the World Bank Governance Indicators. Distributor capabilities can obviously diverge from broader government capabilities and further consultation with individual country experts may be able to identify high capacity regional distributors even in countries with highly ineffective governments. Nonetheless, the data broadly indicates which countries are likely to contain utilities able to implement AMI programmes. Again, India and Pakistan emerge the only clear candidates for this application amongst ICF priority countries (confirmed in Box 8). The other countries with high capacity governments, such as Ghana and Tanzania have extremely high electricity subsidies which, as explained above may make them challenging countries in which to introduce AMI programmes; whereas other low subsidy countries, such as the Democratic Republic of Congo, have among the lowest capacity governments.

Box 8. **Prospective countries for addressing non-technical losses**

India, Pakistan

4.2.5 Conclusions

Table 9 shows the countries prioritised for each of the different applications, highlighting that a range of countries are suitable candidates for multiple applications.

Table 9. **Different ICF priority countries are likely to benefit from different applications**

Country	Smart grid extension	Grid-connected mini-grids	Grid-ready mini-grids	Non-technical losses
India	✓	✓	✗	✓
Ghana	✓	✓	✓	✗
Pakistan	✗	✓	✗	✓
Bangladesh	✗	✓	✓	✗
Nigeria	✗	✓	✓	✗
Ethiopia	✓	✗	✓	✗
Mozambique	✓	✗	✓	✗
Rwanda	✓	✗	✓	✗
Uganda	✓	✗	✓	✗
Tanzania	✓	✗	✗	✗
Kenya	✓	✗	✗	✗
Colombia	✗	✓	✗	✗
Nepal	✗	✓	✗	✗
Cameroon	✗	✗	✓	✗

Source: Vivid Economics and Arup

Each country can be characterised as lying in the middle parts of a spectrum of electricity sector development, running from complete lack of electricity generation and distribution to widespread, centralised access to electricity. The regularity mentioned above arises because the focus of this report, on electricity network interventions, tends to lend itself to application in countries with moderately developed power sectors – at neither extreme of the spectrum.

Simplifying, countries with extremely limited electricity access, such as Malawi and Rwanda, tend to have weak generation, transmission and distribution infrastructure. Demand for electricity is likely to be undeveloped, especially in rural areas. Few productive uses of electricity and no access to appliances imply that the most effective energy access interventions may be promoting off-grid solutions, such as solar lanterns or solar home systems. Interventions that are instead aimed at improving the efficiency of the central grid will have little impact in a country where less than one in five people have access to the network. Isolated hybrid mini-grids are more relevant but, as discussed in Section 2, have not been the focus of this report because of the substantial research already ongoing on their use and deployment. The only priority application considered in this report that naturally lends itself to countries of this type is ensuring that mini-grids are grid-ready, which may be relevant if electricity access is rapidly expanding.

At the other extreme, countries such as China and South Africa already have close to universal access to the grid. While this does not imply that everyone has access to high quality service levels, it does tend to indicate the presence of a utility with reasonably high capacity. The low hanging fruit in terms of improved networks is likely to have already been captured and the role for donor funds such as from the ICF may be limited to promoting applications that are pushing the technical frontier.

The countries identified in Table 9, by contrast, tend to have a partially developed central network with some reliability issues in grid-connected areas, and either incomplete electrification. Typically the grid is unreliable but sufficient to support productive activities if augmented with a generator set. As a result, there are potential gains to technological interventions that would improve grid performance, and there is likely to be demand for such interventions. These countries offer relatively fertile ground for enhancement of network efficiency and some, such as India, Ghana and Pakistan appear on three of the four lists. Engaging country offices in these countries may be a reasonable first step in pushing forward with network interventions. As these countries still have a substantial access challenges to address, off-grid mini-grid and other decentralised energy solutions are also likely to prove a substantial part of future investments in these countries, despite not being a focus of this report.

4.3 Next steps and areas for further investigation

4.3.1 Grid extension augmented with smart technologies

The 'smart' grid extension case studies indicated that relatively high costs and the need for bespoke technical solutions might make widespread applications of this type challenging to deliver in the near term in developing countries. Nevertheless, this study indicates that these areas are of some technical and economic potential with the promise of widespread future adoption, and a broad range of countries might demand these applications if challenges of cost and technical capacity can be overcome. A 'watching brief' on these applications with a view to future implementation of demonstration or commercial projects in developing countries could be easily justified.

Box 9. **Area for future investigation: grid extension augmented with smart technologies**

- A 'watching brief' or further research to collate lessons from the developed world in relation to use of distributed storage, generation and control systems to support grid extension and grid augmentation
- Relatively high costs and the need for bespoke technical solutions might make applications of this type challenging to deliver in the near term in many developing countries

4.3.2 Grid-connected mini-grids

While the potential role of telecommunications towers as an anchor customer for mini-grids is well understood by, and a strong focus for, the development community, the uptake of single-user grid-connected mini-grid approaches has been private sector led and largely escaped the attention of donors and policy-makers. The diverse potential range of businesses that have employed their own capital to install distributed renewable generation, storage and management systems in place of diesel generators suggests a substantial and growing market for these technologies. The breadth of the case studies discussed above suggests a range of applications where the project economics of these applications are favourable. This is likely to increase with expected future cost reductions for both distributed renewable generation and battery storage. The potential market size for hybridisation of diesel generation with either or both of renewable energy and battery systems is reinforced by the Alliance for Rural Electrification's estimate that industrial companies use around 500 GW of power from diesel gensets worldwide (Alliance for Rural Electrification, n.d.).

Given the potential for further private sector-led growth in this area, the challenge for policy-makers, regulators and utilities is to capture the potential network efficiencies from this trend. The single-user mini-grid case studies examined each create a new asset that could, under the right policy and economic settings, be made available to contribute to broader network efficiency. Storage assets can absorb power from the grid at times of grid availability and return it to improve the system balancing. Similarly distributed diesel generators that are not operating at full capacity due to the output of renewable generation could be run at a higher capacity to export power when needed. In general, decentralised uptake of batteries and distributed generation will contribute positively to grid stability and network efficiency when they draw power from the grid when the supply is ample and export to the grid and/or supplying local loads when supply is tight.

Donors could support innovation in business models to capture potential network benefits of mini-grid investments, similarly to their support for business models to expand electricity access through anchor customers. Both the Rockefeller Foundation's SPEED programme and GSMA's Green Power for Mobile programme sought to develop business models that could expand green power and increase electricity access. In a similar manner, donors and policy-makers could play a facilitative role in identifying and implementing commercially viable approaches that could capture wider network benefits from single-user mini-grid investments.

Suitable business models are likely to be important because end users are unlikely to be motivated to address the trade-offs associated with providing both end-user reliability and wider grid stabilisation. It is reasonable to expect that an end user will care only that the chosen energy supply system meets its desired reliability goals at acceptable cost. The trade-offs in system sizing and operation that would arise from also seeking to provide stabilisation services to the network would require substantial expertise in the energy market. Therefore either ESCOs or the utility itself are better placed than end users to support the wider reliability needs of the grid whilst meeting acceptable service standards for the load. Examples of the trade-offs involved are listed in Table 10.

Table 10. **Stabilising the wider grid implies trade-offs with meeting the needs of an end user**

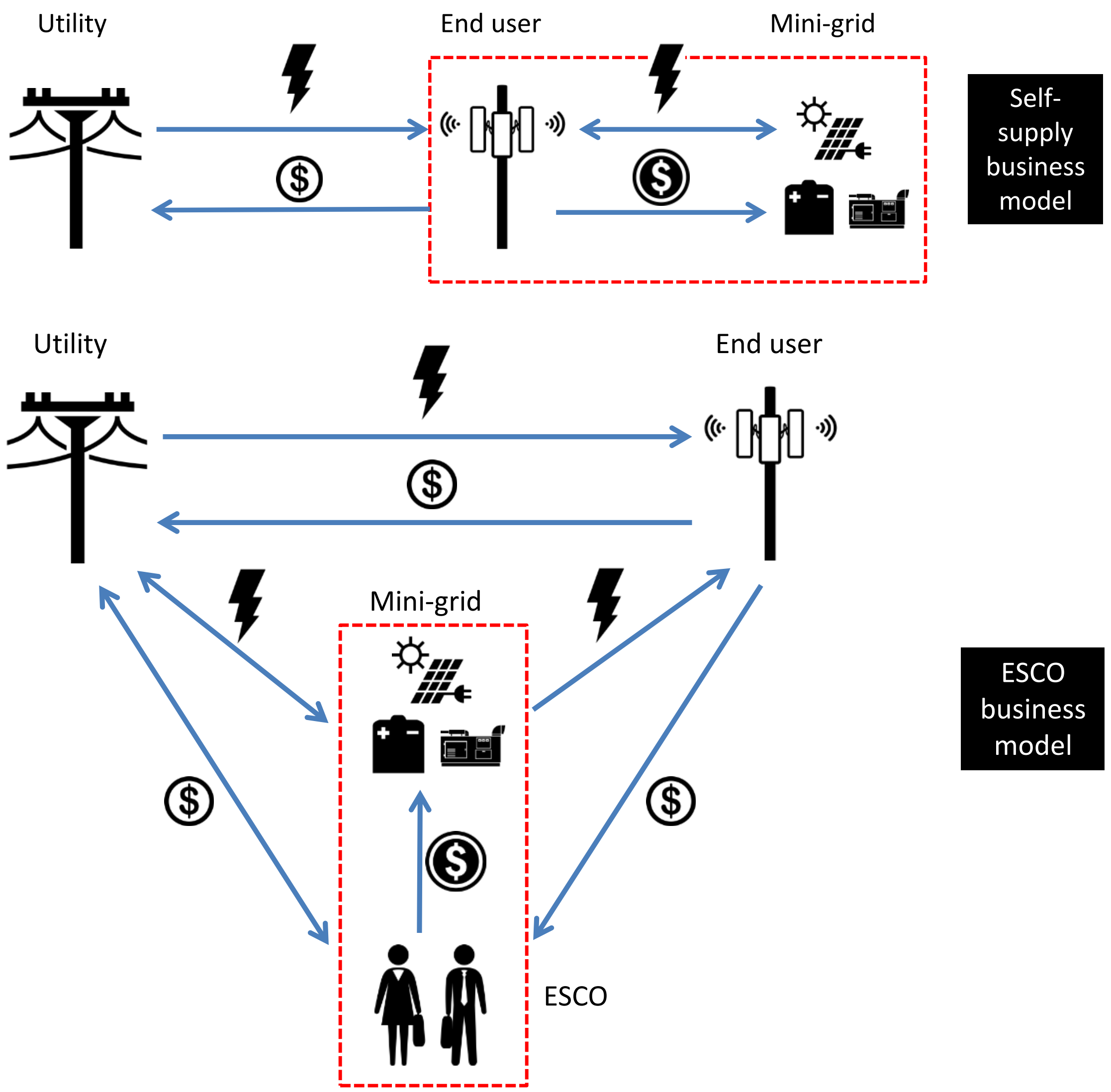
Desired network service	Network requirement	Implication for telecommunications tower
Ramp up (providing extra power to support grid-based generation)	Discharging battery power	Reducing stored battery power increases risk of outage or need for diesel generation
Peak-shaving (providing extra power to support local network)	Discharging battery power	As for ramp up
Ramp down (absorbing power in response to falling demand)	Battery must be held below full charge to absorb excess grid power	Holding battery below full charge reduces stored power, increasing risk of outage or need for diesel generation
Frequency control (absorbing or releasing power to stabilise grid frequency)	Battery must be held below full charge to accommodate small frequency fluctuations	As for ramp down

Source: Vivid Economics and Arup

Successful business models could supply a broad market, including both grid-connected telecommunications towers and a range of other commercial loads. As the case studies examined in this report illustrate, a range of businesses other than telecommunications towers are willing and able to pay for reliability, and are likely to increasingly adopt decentralised energy solutions based on local renewable generation and battery storage. The diversity of these users further emphasises the importance of ESCOs to develop business models and internalise the required expertise, rather than requiring a range of end users to tackle these problems anew in a range of similar but subtly different contexts.

The critical aspect of a business model of this type is to manage operations to provide both ‘reliability services’ to the end user and ‘stabilisation services’ to the wider grid. One potential ESCO business model is illustrated in Figure 14 and contrasted with a ‘self-supply’ approach where storage and renewable generation is installed by the end user solely to meet its own needs. This diagram illustrates the potential for two way flows of energy to stabilise the wider electricity grid and for revenue to flow from both the utility and the end user to the ESCO in exchange for services received.

Figure 14. **An ESCO is better placed to support both end user reliability and wider grid stability**



Note: *Red dashed boxes indicate ownership. Dark money signs indicate a flow of capital. Light money signs indicate a flow of revenue. Lightning bolts indicate a flow of electricity. The end user is depicted as a cell tower for illustrative purposes only; an equivalent business model could apply to a range of end users.*

Source: *Vivid Economics*

Households also use batteries to mitigate the effects of an unreliable grid in a range of developing markets; however they typically prefer systems with low upfront costs and limited technical sophistication. In markets such as India and Kenya, a range of businesses sell small battery packs for back-up household power. These systems usually employ cheap lead-acid batteries with short lives, low discharge depth, limited control features and low conversion efficiency. To illustrate the scale of this issue, poor inverter and battery conversion efficiencies increase greenhouse gas emissions; in India alone the resulting emissions from back-up battery and inverter systems could be almost two million tonnes of CO_2e (Wartsila, 2009).

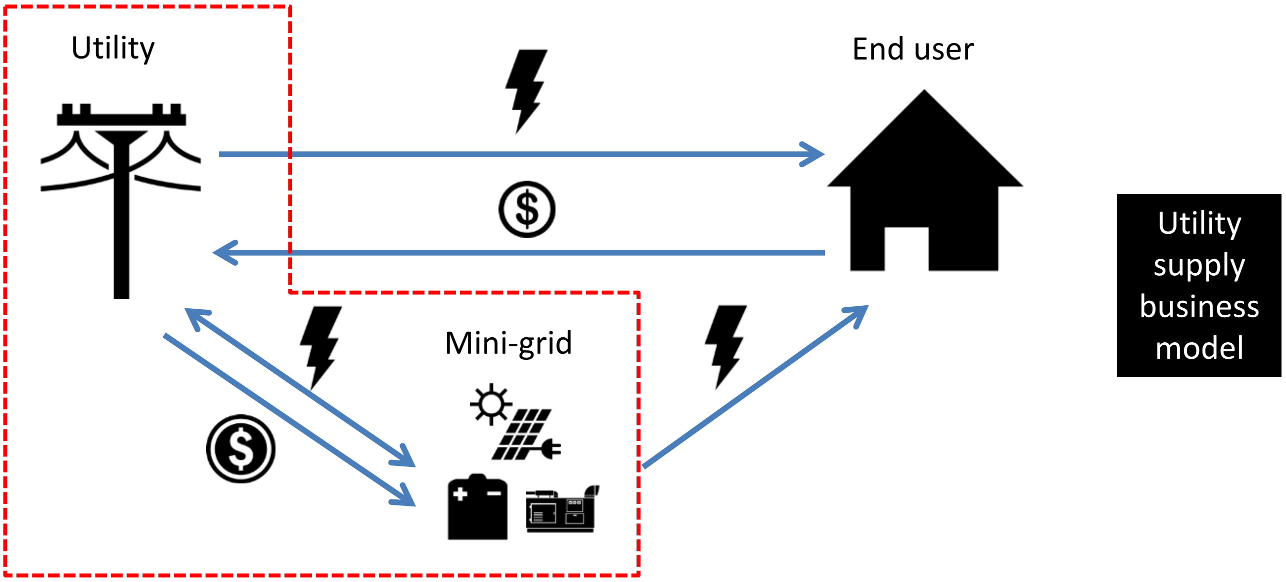
A critical early challenge is not to deploy these battery installations to improve network efficiency, but rather to simply prevent their increasing adoption from degrading network efficiency. For example, a study by authors from IBM Research, Solarsis and Radio Studio in India indicates that widespread take up of back-up batteries by Indian households is already occurring and, rather than supporting network efficiency, actually has negative consequences for grid stability (Seetharam et al., 2013). This occurs because inefficient battery technology and simple control systems result in the batteries charging immediately when the grid returns to service, causing a spike in demand and a drop in system frequency (Seetharam et al., 2013).

A possible mitigating approach to investigate is the employment of direct load control to coordinate the recharging of household batteries. This approach is suggested in the IBM Research, Solarsis and Radio Studio study (Seetharam et al., 2013). Such an approach would not provide for the more sophisticated network services potentially offered by batteries, such as frequency control and peak-shaving. However, controlling when power is absorbed from the grid by networks would avoid artificial spikes in demand and could potentially assist to absorb excess power ('ramp down') when generation levels are high relative to demand. Regulatory approaches to mandate this process may be necessary, and technical assistance to utilities or regulators could assist to understand the implications of this approach.

A more comprehensive approach might be the development of business models where an ESCO invests in batteries and sells 'reliability services' to households as well as 'stabilisation services' to the wider grid. This business model would be conceptually similar to the ESCO business model illustrated in Figure 14. This approach has further advantages in the context of household preferences for systems with low upfront costs; more sophisticated batteries are more expensive than lead-acid batteries but also have substantially longer operating lives. While lead-acid batteries only operate for around 2,000 charge-discharge cycles, more advanced lithium-ion batteries commonly achieve 5,000 cycles (Alliance for Rural Electrification, 2013). A business model where an ESCO or the utility invests in the battery technology and sells a stream of reliability services to the household may support the deployment of more sophisticated, longer-lived batteries with higher capital costs, which in turn are more technically capable of providing sophisticated grid stabilisation services.

A further potential business model for this application would be where the utility itself invests in distributed storage and generation. This business model is illustrated in Figure 15. Compared to an ESCO based approach it has the advantage of internalising many of the variables and simplifying commercial and technical arrangements; however, as it is dependent on the utility driving the business model, it may not drive as much innovation or leverage private finance as a more decentralised ESCO-based model. Such a utility-driven business model could be applicable to larger energy users as well as households.

Figure 15. **A utility-driven business model may be simpler and therefore more feasible for smaller end users**



Note: *Red dashed boxes indicate ownership. Dark money signs indicate a flow of capital. Light money signs indicate a flow of revenue. Lightning bolts indicate a flow of electricity. The end user is depicted as a household for illustrative purposes only; an equivalent business model could apply to a range of end users.*

Source: *Vivid Economics*

In either the household or larger user contexts, donors could support the development of ESCO business models and liaison with utilities to explore opportunities to capture broader network benefits. In the telecommunications towers anchor customer cases, capacity building and stakeholder engagement was necessary to bring together the necessary commercial and technical expertise, while coordinating the needs of a range of stakeholders. Small investments in similar activities in relation to grid-connected, single-user applications could, if successful, unlock substantial private sector investment to enhance network efficiency and end-user reliability.

Box 10. **Area for future investigation: interaction of private and network-wide benefits of distributed storage within grid-connected mini-grids**

- There is a need to develop innovative business models, potentially involving dedicated energy service companies that can utilise mini-grid technologies to provide both 'reliability services' to end users and wider 'grid stabilisation' services could make a substantial contribution to network efficiency
- Capacity building and stakeholder engagement on potential business models could be a high-value contribution of the donor community to network efficiency
- Suitable technical applications and business models could serve both business electricity consumers and households, though different models may be required in different circumstances
- Direct load control may be an alternative measure to manage the negative effects of uncoordinated household battery charging on the grid; technical assistance could be justified to assess the implications of this approach

4.3.3 Grid-ready mini-grids

Technical assistance could enhance local capacity to develop the necessary technical and regulatory standards to ensure grid-readiness, and in turn support investment in mini-grids. The analysis in section 4.2.1 highlights countries where the potential for electricity expansion through off-grid mini-grids is substantial, but where regulatory aspects of grid-readiness are not well developed. Failure to develop aspects such as connection arrangements and standardised power purchase agreements could increase risks for, and reduce finance from, the private sector for mini-grid developments. Socialising existing understanding and research in countries such as Bangladesh, Ethiopia, Mozambique and Rwanda could materially improve the process of access expansion for relatively little effort.

Box 11. **Area for future investigation: regulatory measures for grid-ready mini-grids**

- Technical assistance to countries such as Bangladesh, Ethiopia, Mozambique and Rwanda to develop technical and regulatory standards to support grid-readiness
- Socialisation of research on international experience with regulatory, community and technical stakeholders in these countries

4.3.4 Smart meters and ICT to reduce non-technical losses

This analysis has identified several countries that are plausible candidates for measures to address non-technical losses. While this analysis is not based on data that precisely identified non-technical losses separately from technical losses, and it is difficult to isolate all the political and technical factors necessary to support programmes of this type, India and Pakistan appear to be strong candidates for measures to address non-technical losses.

A potential role for the donor community is to be ready to partner with utilities that wish to address non-technical losses by supporting complementary social programmes. Given the social and political challenges associated with any programme to address non-technical losses, implementing entities would be greatly assisted by measures that alleviate some of these challenges. One role for the donor community may be to undertake complementary investments in energy efficiency, education, local business development or crime prevention as part of a package to support the political and social feasibility of the non-technical losses programme. More detailed examination of the design and delivery of social programmes in the Ampla case study could support this approach in future. Taking that role, it is important for external organisations to develop relationships to allow early identification of opportunities to support and partner with implementing organisations seeking to address non-technical losses.

Box 12. **Area for future investigation: complementary investments to improve the social and political feasibility of addressing non-technical losses**

– Further research into the role of complementary investments, such as energy efficiency, education, local business development or crime prevention, to improve the social and political feasibility of addressing non-technical losses
– Early identification of utilities seeking to address non-technical losses and examination of the potential to partner with and support these utilities through complementary social programmes

4.3.5 Areas for further examination

This study has focused on four potential ways in which network efficiency could be improved; however, other areas may justify further study. The choice of these four applications was driven by a desire to identify areas where strategic efforts using ICF funds, or by other donors or investors can potentially make a large difference to network efficiency. However, other applications will also be attractive under the right circumstances, and further research effort could identify barriers and opportunities in relation to these technologies.

A particular area of interest may be technologies assessed here to have a high value from further research but with limited potential to attract private sector financing. These areas were highlighted in Table 5. Utilities or energy investors with sufficient capital and technical expertise may be well placed to develop or adopt these in appropriate circumstances, and further research and information sharing could highlight these circumstances. The two principal areas of this type are:

– Distributed storage to support the grid (application #9); and
– Smart meters and ICT for outage and general grid management (#13).

Box 13. **Area for future investigation: distributed storage and smart technologies for grid management**

- The use of distributed storage to support the grid and smart technologies for grid management are emerging areas that offer high value from further research
- With prevailing costs and market structures these applications appear unlikely to be funded other than through traditional utility business models and so are less likely to be adopted widely and rapidly, but may be viable longer-term investment options

Appendix A: Technical review material

Grid extension augmented with smart technologies (application #3)

Application overview

'Traditional' approaches to extending the electricity network to unconnected peri-urban or rural areas typically involves transmission and distribution poles/towers, cables, transformers, switchgear and some form of system to monitor and control the network. These components are designed to operate together to deliver reliable power to the new customers within specified voltage and frequency limits while maintaining the stable operation of the existing system.

Potentially a range of smart distributed technologies could be employed to augment such a traditional grid connection, while improving the economies and/or reliability of the grid extension. These technologies could include:

- Distributed storage;
- Distribution automation or 'advanced network management' technologies;
- Distributed generation integrated with network control elements;
- Demand management techniques or technologies.

These approaches can all potentially improve grid extension economics by reducing the required capacity of new lines, transformer and switchgear for the extension, and potentially the scope and cost of upgrades of the network upstream of the new network assets.

The benefits and the associated costs of employing smart technologies in this way need to be considered on a case-by-case basis. In general, while some of these approaches are less capital intensive than a traditional network extension, they are likely to impose additional operational and maintenance costs.

Key technologies

The umbrella definitions 'smart grids' and 'smart technologies' encompass a number of technologies and operational strategies that seek to deliver flexible, affordable, reliable and efficient power. Their key common features are that they are designed for bidirectional energy flows rather than traditional approaches based on unidirectional flows from large generation facilities to final end customers through a centralised network. These smart technologies are almost universally underpinned by communications and ICT technologies to remotely monitor and manage their operation. The core types of technologies are listed below and discussed in turn:

- Distributed storage;
- Distribution automation or 'advanced network management' technologies;
- Distributed generation integrated with network control elements;
- Demand management techniques or technologies.

Distributed storage can reduce the cost of the network by storing electricity when supply exceeds demand and releasing it when needed. This 'peak-shaving' function can reduce the required peak capacity of new network components such as cables and transformers, as well as alleviating stress on the existing network and reducing the need for reinforcement/upgrades. It can also increase the flexibility of the network, for example by smoothing both load variability and intermittency of renewable distributed generation.

Distributed storage can also increase the reliability of a network by supplying local loads in 'islanded' mode in the event of outages upstream of the storage point. The deeper the storage is located within the network, the greater the potential to mitigate the impact on customers of network outages. Distributed storage can even be located on the 'customer side' of the meter or embedded within the grid.

Distribution automation is an umbrella definition covering a range of techniques and technologies that provide more detailed information about the state of the distribution network and allow for more flexible operation and control. This can facilitate greater connection of distributed generation or load while ensuring safe operation of the network. The scope of network control and automation is usually smaller in distribution networks compared to the transmission level. Key elements of distribution automation include:

- Advanced Volt/Volt-Ampere reactive control and optimisation techniques to regulate voltage levels;
- dynamic line rating, where the capacity of power lines is calculated in real-time as a function of the temperature, allowing networks lines to carry more power than their nominal ratings, reducing the need for upgrades;
- dynamic transformer rating operates similarly to dynamic line rating to release additional transformer capacity, reduce losses and defer upgrades; and
- thermal congestion management.

Distribution automation relies on an understanding of the real-time state of the network. As distribution networks have many nodes it is generally impractical to have meters and sensors at each node to measure voltage and current. State estimation is a technique by which measurements at a few points in the network are used to estimate the state of the wider network. State estimation is used to control distribution automation elements described above, such as voltage control and thermal congestion management. Distribution automation approaches require additional communication infrastructure, which entails additional costs.

Distributed generation assets, can be used to provide power locally and reduce the required network capacity (cables, transformers and switchgear) to supply the newly connected loads. However, this generally requires the generation assets to be integrated with broader network control mechanisms such as active network management. Typically distributed generation assets are not network controlled, but within a smart grid style approach described here such assets could either be operated or contracted by the network operator to augment the grid extension, and their effects on network design anticipated and planned for.

Demand response techniques that seek to moderate final users' power requirements can in principle reduce peak demands on network components and therefore the cost of grid extension. However, in the context of a grid extension project this approach must be applied in a way that does not materially compromise the economic benefits of expanding or enhancing electricity access. A range of demand response techniques could be applied including: direct load control where utilities can directly switch on or off specified loads subject to agreement with and compensation of the customer; distributed intelligent load controllers (DILCs) that monitor the system frequency and dynamically disconnected agreed loads as necessary; current limiting at a customer's connection point; or demand response based on price signals.

Key challenges

Grid extension, whether 'traditional' or augmented with smart technologies, is a complex planning exercise that requires careful analysis. A range of design factors can lead to poorly specified investments, including estimating demand, topographical constraints, network operating constraints, limited technical capacity and difficulties associated with balancing load and renewable generation.

Predicting demand and accommodating demand variability and growth is inherently challenging. Off-grid rural communities typically have low disposable incomes and can only afford to use power for small uses, such as lighting, a mobile phone battery charger and possibly a small fridge. Such low power density only generates small revenues and is often insufficient to cover grid extension costs. However, sizing grid connections on the initial (limited) load is a common mistake, as research and practical experience indicates that loads often grow relatively quickly after communities are connected to the grid.

While 'future proofing' the network for demand growth is inherently complex, smart approaches are intrinsically more modular than traditional grid approaches. This can alleviate some of the economic risks and technical challenges associated with serving new electrical loads.

Grid extensions in developing countries often face difficult topographies and distant supply chains to reach remote locations. These logistical challenges can in many locations be exacerbated by poor local security or regional conflicts. These factors can raise the cost of construction and operation and maintenance (O&M) compared with more accessible locations, or make investment in grid extension simply unfeasible. In such a situation even a 'smart' grid extension may be too risky or uneconomic, and more decentralised electricity supply options may be preferred.

Grid extensions often face several challenges in delivering power to final customers at regulated voltage and frequency. Small rural loads can face difficulties in operating within network limits. One problem is 'voltage sag' on long feeders. This can lead to brownouts under conditions of heavy loading. Adding to this complexity, rural areas have local renewable energy resources and the space to install the associated generation and switchgear equipment. While this brings a number of benefits including the provision of local, sustainable and green power to households, business and services, the integration of renewable electricity can increase the design complexity of the network.

In relation to both of these factors, use of distributed storage and advanced network management can address these challenges. However, in turn these approaches may increase the level of technical skills required to install, operate and maintain the grid. These resources may not be available in developing countries, particularly or rural locations.

Technical maturity and timeframe for application

The technical maturity and timeframe for application of the various ‘smart’ technologies and techniques that could be used to augment a grid extension are set out in Table 11.

Table 11. **Technical maturity and timeframe for application**

Technology/ technique	Technical maturity	Timeframe for application
Distributed storage	R&D and successful pilot projects Batteries are readily available on the market	Medium term, due to high but declining capital costs
Distribution automation	R&D and successful pilot projects Some technologies are approaching commercial maturity	Medium term, depending on complexity of the system and local utility network design and operation practice and standards
Distributed generation	Generally technically proven	Short-term, but dependent on local resources and costs
Load control	Basic load limiters are well established and available on the market. Advanced demand response through DILCs is under development with successful pilot projects	Short to medium term, depending on economic incentives and level of complexity of control required

Source: *Vivid Economics and Arup*

Grid-connected mini-grids (Application #6)

Application overview

While electricity access is often a major problem in developing countries, it is also true than connected customers can also face access issues due to poor grid reliability. Even large cities such as New Delhi and Lagos experience frequent and persistent brownouts and blackouts, and can suffer from poor power quality. Unreliable and poor quality power supply affects a range of activities including households, small commercial businesses, manufacturing, public services and critical facilities such as hospitals.

A common response to poor power reliability and quality is the installation of generators, predominantly diesel fired, at the customer’s premises. These generators are run whenever power is lost or degrades substantially in quality. While this solution is technologically simple and relatively reliable, it exposes the user to high and fluctuating fuel costs and harmful combustion emissions in the local area. Given the cost and pollution, not all users choose to adopt this response, and instead go without power during disruptions to grid service.

An emerging response to poor grid reliability and power quality is the installation of a local, grid-connected ‘mini-grid’ that combines distributed generation, storage and smart control systems. These systems can provide a cost effective alternative to solely relying on diesel generators by displacing some diesel use with cheaper renewable generation sources, minimising diesel operation through battery storage of grid electricity and through improving the efficiency of diesel operation by allowing it to operate at more efficient load levels. Smart control systems can achieve enhanced system reliability by integrating renewable and fossil generation sources, managing the availability of battery or fossil energy, and ‘islanding’ users from the grid when faults or outages in the wider network are detected such that the user is electrically disconnected from the grid but continues to receive power from local sources.

Typically a ‘mini-grid’ is defined as local generation, storage and network assets supplying more than one user through a system not controlled by an electric utility. For the purpose of this discussion, we define a grid-connected mini-grid as any combination of non-utility controlled generation, storage and smart controls within a grid-connected system. This inclusive definition captures a wide range of applications, from relatively simple systems serving a single user to more complex multi-user networks.

The key benefits of a grid-connected mini-grid are enhanced reliability, particularly when compared to the reliability of the wider network, and reduced costs compared to a basic diesel generator back-up approach. Use of storage and smart controls to integrate local renewable resources can reduce fuel costs and support sustainable, low emissions energy production. A grid-connected mini-grid can also export excess power from distributed generation sources while managing generation output within the constraints of local user needs.

On the cost side, sophisticated mini-grid applications are typically more capital-intensive than a basic diesel generator approach, and also can have high maintenance costs. Also, the process of obtaining necessary approvals to establish the system with the wider grid provider can be long and costly, depending on the location and approach.

Key technologies

This study adopts a broad definition of a ‘mini-grid’ as local generation, storage and network assets supplying one or more users through a system not controlled by an electric utility. Such a system will include a distribution network of cables, transformers and switchgear to connect power sources, loads and, in some cases, storage devices. For single user examples of this type there will be no ‘distribution network’ as such, other than wiring internal to the customer’s premises.

Generation technologies applicable within a mini-grid application should be available at the required small scale and relatively easy to maintain. The typical fossil fuel technology employed is the diesel generator, though this is increasingly being displaced as small-scale renewable energy technologies (for example PV cells) reduce in cost. Other suitable small-scale renewable generation sources include mini-hydro or biomass gasifiers.

Recent advances in power electronics and control methodologies has allowed the coupling of storage (typically batteries), renewable generation and diesel generators to create a hybrid power system. In such an arrangement the batteries are capable of level load and manage renewable intermittency by storing and releasing energy. This allows the diesel generator to operate at higher efficiency, which is a function of the power produced and is generally highest at above 75 per cent of full load. Advanced control methods can also enable the mini-grid to transfer from grid-connection to 'islanded' (stand-alone) mode in seamless way. Simpler mini-grids can still transfer from one mode to the other but the customers will experience a temporary power cut. Various battery types have been deployed in grid-connected mini-grid applications, including valve regulated lead acid batteries, flooded lead acid batteries, sodium-sulphur batteries, lithium-ion batteries and vanadium redox flow batteries.

Key challenges

The challenges associated with grid-connected mini-grids vary depending on the context. However, these can be broadly categorised as relating to the following: grid interconnection arrangements; technical capacity for installation and operation; mini-grid control systems; and economic viability.

Grid interconnection standards and local utility guidelines generally do not favour mini-grids. Distributed energy supply systems of this type are often seen as a potential threat to the stability and the safety of the existing network. Where the interconnection procedure is long and uncertain, potential adopters of this technology may be deterred.

The availability of technical skills also typically favours diesel generation over more sophisticated mini-grid approaches. Conventional diesel generators are also typically well understood and generally technicians who can repair and maintain them are available. By contrast, it can be challenging in developing economies to find enough technicians who are able to deal with more advanced components like power converters, PV panels and DC switchgear.

The complexity of mini-grid control systems depends on the type of generation and storage involved and on the tasks which the control has to perform. Such tasks include power balancing, diesel efficiency improvement or power quality enhancement. Manufacturers and system integrators offer a number of solutions, and suitable off-the-shelf systems may be available for many applications. However, this will not be true in all cases and it is important to understand at the design stage whether the offered solutions are fit for the purpose or require additional customisation.

The economic viability of grid-connected mini-grids, as with grid extensions and off-grid mini-grids, commonly face a problem of low 'energy density'. Load from rural villages and communities is often insufficient to underpin a grid-connected mini-grid, even if local renewable sources are available, such as hydropower. The anchor customer concept has proven to be a successful way of mitigating this problem. This approach involves finding (or even establishing) a larger electricity 'anchor' consumer (such as an agricultural processing facility or telecommunications tower) that has a well-defined load demand and the capability of paying for the electricity usage. The economies of scale and revenue available from serving the anchor customer, combined with the potential reliability benefit for the anchor customer, enhances the economic viability of the project and the ability to attract private capital to underpin the development.

Technical maturity and timeframe for application

The components involved in establishing a grid-connected mini-grids are generally considered to be technically mature, and components are readily available on the market. Mini-grid control methods are well established and 'standard' solutions are available on the market. However, depending on the application and the customer's requirements, the final control solution might require customisation and further development. In general, grid-connected mini-grids are available for adoption in the short-term, subject to economic viability. Nevertheless, it should be noted that the components are continuing to improve in both functionality and cost-effectiveness. Accordingly, these technologies can be considered mature and broadly applicable now, but are likely to increase in range and scale over time.

Grid-ready mini-grids (application #7)

Application overview

The installation of an off-grid mini-grid is often the most economically efficient way to bring power to communities which are remotely located or are unlikely to consume enough electricity to justify a grid extension. However, over time, electrical access from the mini-grid is likely to support economic development, increase incomes and electricity demand. As demand increases, the economic case for connection to the main grid may become justified.

The process of connecting a previously islanded mini-grid with the main grid raises a range of technical and commercial issues. A 'grid-ready' mini-grid is a mini-grid that has been designed and/or commercially arranged in a way that anticipates and facilitates this interconnection.

Designing a mini-grid to be grid-ready is not costless. A mini-grid operator may need to install additional switchgear and metering at the point of interconnection, allow for additional capacity in switchgear and equipment, provide higher specification protection systems and higher equipment ratings, install additional control functions on generation units, install additional mini-grid ICT and control functions, and ensure higher quality construction and installation of components. The case for anticipating and incurring these costs upfront against doing so at the time of interconnection will depend on the difficulty of retro-fitting suitable equipment after the initial installation, as well as the expected time between commissioning and grid-connection; a key benefit of a grid-ready mini-grid is the avoidance of these retro-fitting costs.

The critical benefit of a grid-ready mini-grid, however, relates to the dynamic incentives created by combined commercial and technical aspects of understanding how the grid will operate in the event of grid-connection. As stated above, off-grid mini-grids can support development objectives and a successful mini-grid may, in fact, accelerate the timetable by which grid connection is attractive by increasing incomes and electricity demand. However, since the operator of a mini-grid is concerned as to their return on investment in the event of interconnection, this may complicate and even prevent the initial development. From this point of view, apart from the technical aspects of being grid-ready, it is critical that policy and regulatory processes provide clarity and certainty for such investments. Key elements of this include standardised power purchase agreements for distributed generators, and clear guidelines and procedures for interconnection.

Key technologies

A 'grid-ready' mini-grid is an islanded system that combines local generation, storage and network assets to serve local load, and which has been designed in anticipation of future grid connection. In common with both off-grid and grid-connected mini-grids, it will comprise a distribution network consisting of cables, transformers and switchgear that connect power sources, loads and potentially storage devices. Generation sources may include renewable sources such as solar PV or wind, and non-renewable sources such as diesel. Off-grid mini-grids utilise storage to manage the intermittent nature of renewable resources and variability of demand.

The mini-grid will operate in an islanded mode until it is connected to the main grid, at which time it will need to transfer to an interconnected, synchronised operating mode. The main difference between these modes is how the mini-grid system frequency and voltage are controlled. In islanded mode, the local generation units take up the role of balancing the produced and consumed power thus maintaining the system frequency and voltage within a specified set of values. This control can be done in a number of different ways and depends on the generation mix within the mini-grid, such as synchronous generators, induction generators and power electronics converters. By contrast, in grid-connected mode, frequency and voltage are controlled by the main grid and the mini-grid generation units must operate within the constraints of the wider grid, including being synchronised with the main grid frequency. Depending on the utility's preference, some local generation units might be required to operate to regulate voltage. This change means that the switch from off-grid to grid-connection requires additional control features to be specified in the mini-grid.

At the time of interconnection, a mini-grid operator needs to address how it will operate in both in grid-connected and islanded mode, and how to switch from one mode to the other. As a single controllable unit, a mini-grid has two transition modes: island forming and grid synchronisation. During the island-forming transition, the mini-grid control has to be designed to support the system frequency and voltage. Any transients occurring by this transition should be sufficiently damped in order to allow the formed islanded mini-grid to reach a new stable operation. Alternatively, island forming can be realized as a disconnection from the main grid and then a 'black-start' of the mini-grid. The transition between islanded and grid-connected modes is controlled so that the mini-grid with all its generation can be safely re-connected and re-synchronised to the grid.

Key challenges

Interconnection standards and the local utilities guidelines do not favour mini-grids. Their operation is often seen as a potential threat to the stability and the safety of the existing network. The interconnection procedure is often long, with unclear guidelines and often it requires a number of system studies which can result in additional costs and possibly network upgrades.

To design a grid-ready mini-grid requires anticipating the potential operating scenarios under which it may operate following interconnection. Depending on the timeframe within which this is anticipated, it can be very technically challenging to accurate define the parameters of different operating scenarios, such as grid-connection, disconnection and synchronization, and incorporate them into the design and the specification of the key components of the mini-grid.

Technical maturity and timeframe for application

From the technical point of view the necessary components to install grid-ready mini-grids are mature and readily available on the market. Accordingly, this application is available in the short-term. However, regulatory aspects of grid-readiness are often not fully developed. Often local utilities interconnection guidelines offer very limited guidance on the topic. Grid-readiness of off-grid mini-grids has not been fully addressed by relevant international standards committees, such as the International Electrotechnical Commission and the Institute of Electrical and Electronics Engineers.

Smart metering and ICT to address non-technical losses (application #12)

Application overview

In electricity supply to final customers, losses refer to the amount of electricity injected into the transmission and distribution grids that is not paid for by users and have two components: technical and non-technical. Technical losses consist mainly of power dissipation in the electricity system components. Non-technical losses consist primarily of electricity theft, non-payment by customers and errors in account and record-keeping.

Non-technical losses represent a potentially avoidable financial loss for the utility, and can have significant effects on the availability and price of electricity in the wider community. Lost revenue from non-technical losses either have to be absorbed by supply companies, with potential consequences for the quality of supply, or be paid for as an implicit cross-subsidy by other consumers.

There are various common causes of non-technical losses. These are: illegal connections to the grid, typically to the low voltage network; tampering with a consumption meter; unmetered or inaccurately metered consumption; and bribery or intimidation of utility employees to avoid metering of or payment for electricity.

Smart metering coupled with effective communication systems via ICT networks can address all the types of non-technical losses listed above. Smart remotely-read meters can allow customers to be directly metered from the point of connection to the medium voltage network, meaning that if theft occurs from the low voltage network it occurs ‘behind’ the meter and therefore is at the expense of the customer rather than the wider network. Remotely-read meters can also be located in secure boxes rather than on the customer’s premises, reducing the risk of tampering. Finally, remote communication of meter data with high quality metering and communication equipment reduces the risk of inadvertent inaccurate billing and complicates any attempts by employees of the utility to collude with customers to reduce billed volumes. In combination with the steps described above, ‘master’ meters located within the distribution network can be used to record flows to separate parts of the network, assisting to monitor flows and losses, including non-technical losses across a wide area and focus attention on where losses are occurring.

As implied by the discussion above, smart metering and remote communications must often be combined with wider changes to the distribution network to effectively combat non-technical losses. Principally these involve increased use of medium voltage distribution lines at the expense of low voltage lines, placement of low voltage lines where used in a way that increases the difficulty of illegal connection, and use of secure pole top infrastructure for switching and metering.

The measures described above imply significant upfront costs associated with re-engineering of distribution networks, installations of new metering and communications infrastructure, and system design. While operating costs can also be reduced by avoiding manual meter reading, the primary benefit of these measures is in increasing billing volumes and therefore revenues.

Key technologies

A smart meter is an electronic device that records consumption of electrical energy and communicates that information at least once a day back to the utility company for monitoring and billing purposes. Smart meters enable two-way communication between the meter and the central monitoring system, allowing a utility to both receive information from the meter and remotely control it, such as for remote connection and disconnection.

Smart meters placed at a customer’s premises can provide valuable data. The meters provide data on energy consumption, imbalance between phase currents, allow prepayment and remote disconnection, and generally provide utilities with a clear understanding of the state of the low voltage system in real-time. In addition, because these meters do not require manual reading, they can be secured with a shield and/or installed at an inaccessible location to prevent tampering.

Concentrator meters aggregate and track data from multiple meters. They can be installed within both the medium and low voltage network to continually monitor energy use and to detect instances of theft. Medium voltage network metering allows grid operators to build a precise history of consumption for blocks of the main load and therefore to identify regions where energy theft is occurring. In the low voltage network concentrator meters are typically installed on the output transformer and work in conjunction with electronic meters at the consumer site. This pairing can quickly identify where losses are occurring, particularly in cases where the home meter has been bypassed, enhancing the traceability of any non-technical losses that are occurring.

Communications infrastructure is also needed to allow smart meters to communicate back to the utility company. This is known as ‘Advanced Metering Infrastructure’ (AMI), and is typically provided through wireless technology.

Key challenges

Use of smart metering to address non-technical losses faces technical, economic and social challenges. These include concerns regarding cost, health, security and privacy. In general, the key to successful smart metering systems is balancing the technical design with social aspects of its introduction; without either the program could fail and not produce the required result.

Users are often concerned that the cost of the meter and AMI will eventually be reflected in the end-user bill. While this is often true, a reduction in non-technical losses and the corresponding increase in revenues will generally easily cover the cost of the system installation. A range of AMI case studies demonstrate paybacks in the range of one to five years (World Bank 2011), indicating strong project economics. Nevertheless, it should be expected that users that have been illegally accessing free electricity would not be supporting of measures of this type.

Health concerns have been raised in relation to the meters' wireless communication. Several studies indicate that this should not be a concern such as studies by the California Council on Science and Technology and the Australian Government. Furthermore, a range of marketed products have satisfied relevant environmental and health standards. Residual concerns may be reduced further if meters and/or communication equipment are installed outside the home.

Understandably, end users have concerns over smart meter data privacy. In particular, people may be concerned that data will be provided to law enforcement agencies. The best way to mitigate against this is to educate end users on the purpose of the system and to ensure privacy is dealt with in end-user agreements.

Technical maturity and timeframe for application

Smart meters are a proven technology for which a range of products are marketed and available in the short-term, although functionality and cost continues to improve. Adjustments to distribution network design are generally specific to a given network and so are not an 'off-the-shelf' technology, but their principles are well understood. This approach can be considered as mature and therefore available in the short-term.

Appendix B: Case studies

Case study descriptions for application #3: Grid extension augmented with smart technologies

Two case studies from distinct but analogous applications

Vivid Economics and Arup were unable to identify case studies that directly addressed this application, in which the costs of grid extension are reduced and/or its performance improved through applications of various smart distributed technologies. As discussed above, these technologies range from distributed generation and storage to more complex systems for distribution automation.

However, we were able to identify applications where similar 'smart' technologies were applied to avoid costs associated with upgrading the existing grid. These applications are analogous to application #3 in that smart technologies are used to substitute for and reduce the cost of traditional fixed line network infrastructure, as well as potentially enhancing the operation of that network.

The first case study (Table 12) involves advanced system management techniques, including real-time generation control, dynamic line rating and state estimation to accommodate more distributed renewable generation whilst avoiding network augmentation. Technologically it is similar to application #13 which covers a range of uses of smart ICT technologies for grid management. Consistent with the assessment of smart meters and ICT for grid and outage management in Table 4 this case study was principally utility funded, with public assistance, but the technical, policy and economic aspects remain relevant to understanding application #3.

The second case study (Table 13) involves the use of distributed storage to avoid network augmentation. This application operates similarly to the application described as decentralised storage in Table 3 and Table 4. Again the case study projects were principally utility funded with public assistance, consistent with the assessment of decentralised storage in Table 4. Nevertheless the technical and economic aspects of using distributed storage to avoid network expenditure will assist with understanding application #3, which has a similar objective.

Table 12. **Case study #301: Orkney Islands smart grid (Scotland, United Kingdom)**

Element	Detail
Funding organisation	Initial technology trials were funded by the UK Government's then Department of Trade and Industry in 2004. Further development activities through a trial phase from 2006 were funded by Scottish and Southern Energy Power Distribution (SSEPD) based on regulatory financial incentives. SSEPD delivers electricity to 740,000 customers in the north of Scotland, as well as operating other distribution and transmission networks.

Element	Detail
Implementing organisation	Smarter Grid Solutions, a spin off company formed using technology developed collaboratively by the University of Strathclyde and SSEPD.
Description	Orkney is an archipelago in northern Scotland with a population of around 20,000. Orkney's power needs are met by mix of wind, wave and tidal generation, as well as power delivered from the mainland via two subsea 33 kV cables. Local renewable power resources are high quality (especially wind and wave) making additional renewable power generation capacity attractive, but their variability poses a challenge for managing the grid. Following the installation of an advanced protection system, the total hosting capacity of the Orkney distribution network was raised to 48 MW. However, under prevailing grid connection rules an additional subsea cable (with a cost of around £30 million) and internal island upgrades would have been required in the event of additional generation connections in order to 'accommodate' the potential generation output in a circumstance where the output is uncontrolled (Smarter Grid Solutions, n.d.). In the face of this substantial cost, alternative approaches were required to allow further renewable connection. The deployment of a distribution automation system known as Active Network Management (ANM) in Orkney was implemented to increase the hosting capacity of the network without upgrading expensive network components. This is achieved by the ANM system reducing distributed generation output when the grid is under stress. It achieves this by monitoring the state of the network in real time and controlling its operation in order to satisfy voltage and thermal limits. The further increase in hosting capacity is evidenced by the increased in total distributed generation capacity to 77 MW. This level of generation meant that Orkney was a net exporter to the mainland grid in 2013.
Electricity market structure	Unbundled and liberalised with private participation in all parts of the supply chain
Project status	The ANM has been successfully operating since 2009. The project evolved in three main phases (Macleman, n.d.): - A trial from November 2006; - Connection of additional generation from November 2009; - Ongoing improvements in the AMN scheme since that time, including energy storage and demand side management.
Project objectives	The key objectives of the project were to connect more renewables to take advantage of good local resources, without triggering a need for additional network expenditure, while managing the system within operational constraints.
Key technologies used and techniques applied	ANM technology was used to maximise the utilisation of the existing grid assets and integrate considerably more intermittent renewable electricity within the distribution network. A number of monitoring and control functions are embedded in the installed ANM: - Thermal congestion management; - Voltage control; - Real-time generation control; - Dynamic line rating; - State estimation; and - Demand side management.

Element	Detail
Outcomes, barriers and successes	Technical: ANM now manages the electricity network by monitoring the real time capacity of the grid and reducing distributed generation output when the grid is under stress. Real-time monitoring of the network is underpinned by very high frequency radio communication from several sites across the network. Most technical problems to date have been due to faults in the communication system. This has been addressed by moving to a microwave communication system and installing a backup system. Policy: SSEPD indicates that incentives created under the 'registered power zone' (RPZ) and 'innovation funding incentive' (IFI) were critical to financing the trial phases of the project. The IFI provides funding for research and development, while the RPZ are intended to support greater connection of distributed generation (Southern Energy Power Distribution, 2013) Economic: The ANM system saved approximately £30 million in network reinforcement and allowed the renewable generators to connect within significantly reduced timescales. The Orkney Islands now have over 77 MW of connected generation and have become a net exporter of electricity in 2013. 103% of electricity demand was met by renewable generation and 40% of this was managed by the ANM system. This delivered a £4 million benefit to the local economy (Smarter Grid Solutions, n.d.).
Abatement outcomes	Not quantified. The scheme has enabled the installation of renewable energy sources therefore reducing the emissions generated from the power production.
Key sources	(Smarter Grid Solutions, n.d.) (Macleman, n.d.) (Southern Energy Power Distribution, 2013) (Xero Energy, 2014)

Source: *Vivid Economics and Arup*

Table 13. **Case study #302: Peak-shaving in American distribution networks (United States)**

Element	Detail
Funding organisation	American Electric Power (AEP), a US electric utility that serves 5 million customers in 11 states; US Department of Energy Sandia National Laboratories (Charleston project only)
Implementing organisation	S&C Power Systems Services, a subsidiary of S&C Electric Company, a private engineering company specialising in advanced storage for stationary energy.

Element	Detail
Description	Five projects across four states were implemented on a 'turnkey' basis by S&C Power Systems in conjunction with AEP. The locations were: - Presidio, Texas - Charleston, West Virginia - Milton, West Virginia - Bluffton, Ohio - Churubusco, Indiana Each project involved the installation of batteries 'deep' within the distribution network to reduce expenditure on network upgrades. This was achieved because peak load on transformers or lines within the network could be reduced by charging the battery at off-peak times and discharging at times of higher load. The projects were also intended to improve the company's ability to meet reliability targets by supplying local customers in the event of an outage, while 'islanding' users while the network is under repair. Islanding involves electrically disconnecting part of the network so that it can continue to receive power from local sources irrespective of the status of the wider network, such as when the wider network is de-electrified and under repair.
Electricity market structure	Unbundled and liberalised in Ohio and Texas; vertically-integrated and operating under rate of return regulation in West Virginia and Indiana. Private participation in all parts of the supply chain in all four states.
Project status	Five projects completed between 2006 and 2010.
Project objectives	'Peak shaving', that is, reducing the peak load on transformers in the distribution network to avoid augmentation and reduce wear and tear; 'islanding' to increase reliability for end users being served by the battery.
Key technologies used and techniques applied	75.2 MWh (11.2 MW peak discharge) of battery capacity over five sites, using sodium-sulphur batteries; control systems including 'active dynamic islanding' which is switches supply to battery discharge to supply local customers in the event of a network outage.
Outcomes, barriers and successes	Technical: The DOE's review of the project on its Global Energy Storage database indicates that the Milton project minimised disruptions during a December 2009 snowstorm that islanded 25 customers for over two days. During this time, these customers experienced less than three minutes of disruption to service. AEP indicated that its first project (commissioned in 2006) had operated successfully over its first three full years of operation (Bjelovuk, 2010). In general the hardware appears to have performed as intended at each installation. Policy: While the 2006 Charleston installation was reliant on public funding to be viable (Nourai, 2007) subsequent projects have not required public funding for research, demonstration and deployment purposes (DOE Energy Storage database). Economic: Although AEP and E&C indicate that installations of this type can capture benefits in the form of energy arbitrage, frequency regulation and dynamic VAR support, the primary economic driver of the projects appears to have been transmission and distribution capital deferral. These projects appear unlikely to have been economic in the absence of DOE support for the purpose of technology demonstration. AEP indicates that energy storage cost is still high, and that it is challenging for utilities to capture the full value of energy storage so as to make such projects viable (Weaver, 2014).

Element	Detail
Abatement outcomes	Not quantified. AEP (2010) indicated that peak shaving at the Charleston substation had reduced oil temperatures in the supply transformer by around 4 degrees Celsius. This is likely to have reduced transformer losses. AEP (2010 also emphasises the potential benefits of 'firming and shifting renewables' in the installations, promoting the long-run take up of low emissions generation.
Key sources	(Nourai, 2009) (Nourai, 2007) (Bjelovuk, 2010) (Weaver, 2014) (Nourai & Kearns, 2010) DOE Global Energy Storage database

Source: *Vivid Economics and Arup*

Case study descriptions for application #6: Grid-connected mini-grids

The case studies examined in relation to this application consist of:

- two case studies where an anchor customer underpins the development of a grid-connected mini-grid; and
- five case studies involving single user 'mini-grids' that have adopted various combinations of fossil and renewable distributed generation, batteries and control systems to mitigate the effects of an unreliable grid connection.

The two sets of case studies are grouped due to their similarity.

Anchor customer approaches to grid-connected mini-grids

Table 14. **Case study #601: DESI Power (India)**

Element	Detail
Funding organisation	DESI Power is a developer focusing on the installation of biomass gasifiers in rural communities with limited access to the grid or extremely poor reliability.
Implementing organisation	DESI Power
Description	DESI Power has completed five biomass gasifier based mini-grids between 1996 and 2012, totalling 260 kW and serving over 400 residential and 30 commercial customers in the Bihar region. The DESI Power business model depends upon the identification or development of anchor consumers to provide regular energy demand. These commercial consumers are provided with electricity through the biomass gasifier on a metered basis. Micro-grids are built around these anchor consumers to provide electricity to unserved residential consumers on a flat tariff structure.

Element	Detail
Electricity market structure	Unbundled, but state-owned and not liberalised at the retail level. Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. No private participation except in the generation sector.
Project status	On-going business but slow growth, with projects completed in 1996, 2002, 2006 (two projects) and 2012. All projects remain functional and operating
Project objectives	To increase access to and improve reliability of electricity, thereby generating local employment, developing local businesses and empowering women.
Key technologies used and techniques applied	Biomass gasifiers with capacities ranging from 30 to 100 kWe. These plants can run on crop residues, including rice husk briquettes, but have, to date, largely used dhaincha (a local weed), ipomea and firewood as feedstock. Individual meters are used for commercial customers, with the biomass gasifier located near the production site. Low voltage distribution networks and community level meters are used to provide and monitor electricity for residential consumers.
Outcomes, barriers and successes	Technological: Detailed feasibility studies are needed to guarantee local resources can meet demand. However, the DESI case studies appear to have sufficient local resources to meet demand. Renewable energy systems tend to require skilled labour for maintenance. Biomass gasifiers, for instance, are vulnerable to technical problems such as tar build-up, wet feedstock or failure of electrical components. DESI's success is partly associated with their diligence in management regular site visits to monitor feedstock supply, carry out maintenance, investigate customer theft and check operator logs. Telecommunications systems enable part of this support to be done remotely. Although a carbon neutral technology, power production from biomass gasifiers has a number of waste products like ashes, by-products from gas cleaning and local air pollutants that need to be carefully managed and disposed. Policy: Limited cooperation with local grid company has seen some duplication of distribution infrastructure, with mini-grids operating completely in parallel with the distribution network leaving some existing infrastructure unused. Economic: Use of anchor customers underpins supply to smaller users that may not otherwise be economic to supply. Local entrepreneurs purchase power from DESI Power to retail to small customers. Biomass gasifiers, can have secondary economic benefits by creating additional revenue for farmers selling waste products such as rice husks. All supply chains are vulnerable to demand and supply dynamics.
Abatement outcomes	Not quantified. Abatement will be delivered through use of carbon neutral generation based on biomass gasifiers as an alternative to higher carbon intensity grid-based power. However, given limited grid availability in targeted areas, abatement is likely to be limited.
Key sources	(Schnitzer et al., 2014) (Centre for Development Finance, n.d.)

Source: Vivid Economics and Arup

DESI Power demonstrates the gains to augmenting an unreliable central grid with an improved local mini-grid. Its operations are based in Bihar, which is largely grid connected but which provides an extremely poor quality of service. Power is often available for only two hours per day (Schnitzer et al., 2014). This is insufficient to encourage investment in productivity enhancing equipment for local agribusiness. To the extent that electricity was used prior to micro-grid construction, reliability was provided through expensive and inefficient diesel generators.

The business model utilises anchor consumers to underpin demand. Each of the biomass gasifiers provides electricity for either agribusinesses or telecommunication towers. These high demand users are individually metered and charged on a per unit basis. They both generate the majority of revenue for the micro-grids and require relatively low expenditure on distribution and tariff collection.

Finding an anchor customer appears crucial to the success of the business model. The capital cost of a 75kWe gasifier is around $70,000, with an additional cost of production of around $0.13 per kWh. The pricing strategy for residential consumers is left to local entrepreneurs who purchase power from DESI Power and organise distribution, so the model for recouping these costs cannot be easily summarised. However, indicative estimates garnered through interview suggest pricing of around $0.08 per day per 60-watt electricity bulb, of which DESI Power receives around $0.05. To recoup the initial capital costs without an anchor customer would therefore require 1,400,000 days of light bulb use to be purchased, indicating the difficulty of justifying the investment through residential consumers alone. Income from non-anchor customers is further limited by low demand and ability to pay, and theft further erodes the profitability of extending access. Average incomes in the villages served by the micro-grids are rarely above $50 per month and population densities are low. DESI Power also estimates that as much as two to three kWh are stolen per day at certain sites. Metering is at the community level, which limits the ability to identify theft.

These limitations imply that scaling up requires the active development of anchor consumers, but progress on this front appears to have been limited. DESI Power sister organisations, DESI Mantra and Baharbari Odhyogik Vikash Sahkari Samiti (BOVSS), were set up with the express intention of developing local businesses to support micro-grids, but the business model seems to have increasingly shifted to identifying existing businesses instead.

Further, despite the presence of the central grid throughout Bihar, the benefits of integrating the mini-grids' operation with that of the regional grid does not seem to have been realised. Electricity does not appear to be sold to the regional grid, which could absorb excess generation and act in a similar manner to the grids' anchor customers. The micro-grids also appear to be being run in parallel with existing distribution infrastructure, some of which is unused. DESI Power claims that government cooperation has been limited.

Table 15. **Case study #602: Mwenga hydro plant and mini-grid (Tanzania)**

Element	Detail
Funding organisation	The European Union via the ACP-EU Energy Facility and the Tanzanian Government's Rural Energy Agency (REA) established under the Ministry of Energy and Minerals. The project is registered under the Clean Development Mechanism to provide an additional source of revenue.
Implementing organisation	Rift Valley Energy (RVE), a subsidiary of the Rift Valley Corporation, a diversified agro-industrial enterprise; the Mufindi Tea and Coffee Company; and the Tea Research Institute of Tanzania.
Description	Rift Valley Energy constructed a 3.5MWe hydro power plant on the Mwenga river. The generation is intended to serve the nearby Mufundi Tea and Coffee factory, which acts as an anchor customer. In addition, electricity is distributed to a number of local communities located on the power line route connecting the plant and factory and exported to the national grid.
Electricity market structure	Vertically-integrated and state-owned. No liberalisation at the retail level. All elements of the supply chain integrated within the state-owned Tanzania Electricity Supply Company (TANESCO).
Project status	Operational since September 2012
Project objectives	To increase access to and reliability of electricity and reduce emissions.
Key technologies used and techniques applied	3.5MWe hydro plant underpinning network extension to 14 villages and involving 120 km of distribution lines. Cell phone based pre-paid vending system is used for all consumers.
Outcomes, barriers and successes	Technological: The hydro plant has adequate needs for the anchor customer and village supply, with ample supply for export to the national grid. The hydro plant is a 'run-of-the-river' type and operates by diverting water off the main river through a 340 metre long pipe to the power house. The plant was designed for a 7cubic meter per second water flow rate and because of seasonal variation drops below this during three months of the year. To mitigate against the effects of this, a Francis type turbine was selected which can operate at flow rates 40 per cent below rated flow. To address bill collection difficulties, especially during rainy seasons, residential consumers are fitted with pre-paid meters that can be charged using their mobile phone. Policy: Tariffs are aligned with the national tariff structure. Grid connection and PPA arrangements for the hydro plant were facilitated by standardised connection arrangements for small power producers. Economic: The hydro plant and extension to new villages was underpinned by an anchor customer and substantial exports to the national grid (around 75 per cent of total output). Expansion to further villages and tea operations are expected, which would reduce the volume of exports to the national grid. Costs of grid-connection are charged to residential users upfront, but can be financed through a zero interest loan. Household wiring costs must be funded upfront but are reduced through providing 'readyboards' for household use. It is not clear whether upfront connection costs have slowed grid expansion.

Element	Detail
Abatement outcomes	11,000 tCO_2e per year of abatement from displacing fossil fuel generation serving the Mufundi Tea and Coffee factory and the national grid. The emissions reductions from displaced diesel generation among households is not known due to data limitations, but may also be significant.
Key sources	(Clean Development Mechanism Executive Board, 2006) (Gratwicke, 2013) (Tenenbaum, Greacen, Siyambalapitiya, & Knuckles, 2014)

Source: Vivid Economics and Arup

Like DESI Power, the Mwenga hydro plant also uses an anchor customer approach. Around 3,000 MWh per year is exported to the Mufundi Tea and Coffee factory alone. While this only represents a fraction of the plant's output (which is expected to be around 25,000 MWh per year), it provides a reliable revenue stream that may be invaluable in the earlier stages of the project.

However, Mwenga hydro appears to have been more successful in realising additional revenue streams than DESI Power micro-grids. Electricity is exported to the grid, local community buildings and residential consumers. Each group contributes to the financial sustainability of the project. The plant expects to export 18,500 MWh per year, more than six times the quantity sold to the Mufundi Tea and Coffee factory, to the national utility. This was facilitated by recent changes made by the state utility, TANESCO, to small power producer regulations. These changes have led to standardised interconnection, PPA and tariff agreements, greatly simplifying the process of grid connection. Mwenga hydro was the first greenfield project to take advantage of this new regulatory structure.

Tariff collection could be particularly challenging in the Mwenga context, but this is addressed through mobile phone based payment approaches. Infrastructure is limited, consumers have low incomes and theft is difficult to monitor. Official estimates suggest that 2,600 households across 14 villages will be connected to the micro-grid. During rainy seasons, roads can become impassable. To tackle these challenges, residential consumers are fitted with pre-paid meters that can be charged using their mobile phone. Customers each have a unique meter; they top-up their meter either by purchasing cards from local vendors and sending details through the mobile network or by paying for top-up directly through an M-Pesa account. Tariffs are aligned with the TANESCO national tariff at 4 cents per kWh for any household customer who consumes less than 50 kWh per month (Tenenbaum et al., 2014).

Consumers are expected to cover connection costs. This has been set at $113 for the first 2,600 connections, and will increase thereafter. Consumers for whom the cost is a barrier can pay in stages, with a zero interest loan used to cover the majority of the upfront expense. Consumers must also pay the upfront cost of basic wiring of approximately $56 per household, but can use 'readyboards' provided by Mwenga at a slightly lower cost (Tenenbaum et al., 2014). While providing this financial support could be expensive, requiring an upfront commitment from the consumer helps mitigate the higher costs of installing individual pre-paid meters. It is not clear whether the upfront costs of connection have substantially deterred customer connection.

Single-user grid-connected mini-grids

Table 16. **Case study #603: PV/diesel hybrid mini-grid for a cotton mill (India)**

Element	Detail
Funding organisation	Alpine Knits cotton mill, Palladam, Tamil Nadu, India.
Implementing organisation	SMA, a German engineering company (system integration and engineering); Chemtrols Solar Pvt Ltd, an EPC contractor (solar panels)
Description	Alpine Knits cotton mill has operated a 1.25 MW diesel generator to maintain reliable power supply in the face of daily grid failures. To maintain this reliability while reducing fuel costs and greenhouse gas emissions, this diesel system was converted to a hybrid diesel-solar generation system with integrated management.
Electricity market structure	Partly unbundled, but state-owned and not liberalised at the retail level. Transmission is unbundled from generation, distribution and retailing functions. Non-transmission functions remain bundled within the monopoly Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO). No private participation except in the generation sector, with private power projects supplying TANGEDCO under contract.
Project status	PV installed in June 2013
Project objectives	Reducing fuel costs and greenhouse gas emissions
Key technologies used and techniques applied	1 MW of solar panels, 44 Sunny Tripower inverters and 'SMA Fuel Save Solution' controller integrated with existing 1.25 MW diesel genset
Outcomes, barriers and successes	Technological: During peak production hours the PV systems provides approximately 60 per cent of the total power demand for the mill. The PV system was coupled with existing diesel generators to operate as an integrated hybrid system, and to operate reliably even when the grid fails. Policy: No specific policy factors identified Economic: The rising price of diesel made running diesel generators increasingly expensive. Substantial fuel savings could be achieved from the avoidance of around 450,000 litres of diesel consumption per year. Expected payback periods or rates or return have not been published for this case study.
Abatement outcomes	Estimated 1.2 kilotonnes of CO_2 per year due to reduced diesel consumption
Key sources	(Alliance for Rural Electrification, n.d.) (Fischmann, 2013) (SMA Solar Technology, n.d.)

Source: Vivid Economics and Arup

Table 17. **Case study #604: Batteries to support solar-powered ATMs (Lagos, Nigeria)**

Element	Detail
Funding organisation	Diamond Bank, a large full-service bank in Nigeria
Implementing organisation	Eauxwell Nigeria (water and renewable energy engineering company based in Lagos, partnering with Grunfos A/S Denmark); The Solar Shop Ltd (systems integrator); Trojan (battery supplier)
Description	Nigeria suffers from poor power reliability, with power outages occurring on a near daily basis and lasting up to eight hours. To maintain reliable electricity supply Diamond Bank had used diesel generators to operate ATMs related equipment such as CCTV, alarms and surveillance cameras in the financial centre of Victoria Island, Lagos. The increasing cost of diesel generation motivated a move to use solar power and deep-cycle batteries to reduce diesel generation.
Electricity market structure	Unbundled and partially privatised, but not liberalised at the retail level. Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. A substantial privatisation programme is underway in which the transmission element and some generation assets will remain state-owned but the bulk of Nigeria's generation assets and 11 distribution companies will be privatised.
Project status	Commissioned in 2013
Project objectives	Reducing diesel use and emissions
Key technologies used and techniques applied	35.5 kWh capacity deep-cycle flooded lead acid batteries (Trojan); 3.5 kW Solar World solar panels from AG Solar; SMA Sunny Island inverters

Element	Detail
	The system has been designed to completely eliminate use of diesel generation. The flooded lead acid batteries benefit from a shorter recharge time and longer useful life (8 to 9 years) than valve regulated lead acid batteries (VRLA). However, a drawback is the need for distilled water re-filling and their hazardous nature because charging releases highly explosive hydrogen, whereas VRLA batteries are virtually maintenance free. The batteries were chosen to operate in partial states of charge for extended periods of time, and to be robust to frequent deep discharge and recharge cycles, as required due to the generation cycle of the PV system
Outcomes, barriers and successes	Policy: From 2012, the Nigerian Central Bank has been pursuing a 'cash-less Nigeria' policy, aiming to reduce the amount of physical cash circulating in the economy. This is intended to reduce the costs associated with cash handling throughout the economy, encourage financial inclusion and stymie corruption. The main policy adopted to encourage this shift is a charge on individual daily cash withdrawals above 500,000 Nigerian nairas (around $3,000), which has increased demand for ATMs as a larger number of small volume withdrawals are now made. Economic: Flooded batteries are lower cost than valve-regulated lead-acid batteries. The combination of battery size and technology and solar capacity was considered to provide the best return on investment for this need.
Abatement outcomes	Not quantified precisely, but project descriptions indicate that diesel use will be eliminated entirely.
Key sources	(Trojan Battery Company, n.d.) (Garcia, 2013)

Source: *Vivid Economics and Arup*

Table 18. **Case study #605: Solar power and battery storage to support grid connection (Cap-Haitien, Haiti)**

Element	Detail
Funding organisation	Haiti Hospital Appeal, a UK based charity
Implementing organisation	Onboard Energy, a UK based remote power supplier (system design and installation); Victron Energy, a Dutch technology company specialising in independent applications for marine, industrial, automotive, telecommunications and off-grid power (batteries)
Description	The Haiti Hospital Appeal-run charity had faced power reliability difficulties prior to the Haiti earthquake. After the earthquake reliability became so poor that the charity decided to install an independent power system. A hybrid solar-diesel system with battery pack was determined to best meet the hospital's needs.
Electricity market structure	Vertically-integrated and state-owned. No liberalisation at the retail level. All elements of the supply chain integrated within the state-owned Electricité d'Haiti, other than some private generation providers.
Project status	Complete

Element	Detail
Project objectives	Improved power reliability; reduced diesel fuel use
Key technologies used and techniques applied	Batteries (48 V, 1500Ahr, or approximately 72 kWh), inverter/charger pack (25 kVA), 12 kW of solar panels and 40 kVA diesel generator.
Outcomes, barriers and successes	Technological: The system is designed so that when grid power is lost the battery pack coupled with the PV meets demand and, when needed, the diesel generator is started automatically. The inverters are also able to synchronise with the grid, allowing the batteries to operate in grid-connected mode. Policy: No specific policy factors identified Economic: Company documents indicate a payback period for the system of 'months rather than years', indicating robust project economics. Off Grid Energy also claims that the hospital's diesel costs of around $4,000 per month have been reduced to a fraction of that amount.
Abatement outcomes	Not quantified precisely but company brochures indicate substantial reductions in diesel usage
Key sources	(Offgrid Energy, n.d.) (Victron Energy, n.d.)

Source: Vivid Economics and Arup

Table 19. **Case study #606: Telecommunication towers with battery storage (India)**

Element	Detail
Funding organisation	Not specified, presumed to be funded by the telecommunications company
Implementing organisation	Imergy Power Systems
Description	Reliable energy is critical to the operation of telecommunications towers, and energy supply is a key cost. This is especially the case in remote areas with limited or no grid connection and where diesel generation is required to meet power needs. Imergy replaced existing valve regulated lead acid batteries with longer lasting vanadium redox flow batteries integrated within a sophisticated energy storage platform. The batteries were replaced at three telecommunications towers in India with weak grid access (zero to six hours of supply per day). The new storage platform uses the batteries as the primary source of power in the event of a grid outage, reducing the reliance on diesel generation and increasing the efficiency of diesel operation when needed. In combination, these two effects significantly reduce diesel usage.
Electricity market structure	State locations are not disclosed, but in most Indian states power supply is partly unbundled, but state-owned and not liberalised at the retail level. Generally, distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies, and there is no private participation except in the generation sector.

Element	Detail
Project status	Completed
Project objectives	Improving reliability and reducing fuel use.
Key technologies used and techniques applied	Vanadium redox flow batteries control system; diesel generator (assumed pre-existing)
Outcomes, barriers and successes	Technological: Diesel generators require high levels of utilisation to perform well. Low loads both increase fuel usage and encourage ‘coking’ inside generators, reducing the asset’s lifetime. Effective storage solutions can therefore significantly reduce both costs and fuel usage. By allowing diesel generators to be consistently run at high loads, storage reduces fuel consumption. In this application, the battery system was configured to act as the back-up source in the event of a power cut. Only once the battery was run down would the generator be started, with the generator then run at a high, efficient load to both power the transmitter and charge the battery. When the grid is available, batteries can also draw electricity down from the grid, further reducing the need for diesel generation. Vanadium redox flow batteries are composed of two tanks of negative and positive electrolytes which flow through a stack of power cells discharge and charge periods. Relative to lead-acid batteries, these batteries benefit from longer lifetimes, rapid response times and flexible scaling of storage (determined by the size of electrolyte tanks) and power rating (determined by the number of power cells . Policy: No specific policy factors identified Economic: Project implementers claim payback period of two to three years for all three sites, as well as improving the lifespan of generators. This reflects substantial diesel savings of 37 per cent to 85 per cent and the high cost of delivering diesel to remote sites.
Abatement outcomes	Substantial (proportional) diesel fuel savings, from 37 per cent to 85 per cent. However, these reductions would likely be achieved in part through increased draw of power from the grid, resulting in an increase in emissions from grid electricity.
Key sources	(Imergy Power Systems, n.d.)

Source: Vivid Economics and Arup

Table 20. **Case Study #607: Battery storage for petrol stations (Nigeria)**

Element	Detail
Funding organisation	Oando, a large petrol station operator in Nigeria
Implementing organisation	Corvus Energy Africa Limited, a partnership between Corvus Energy, a Canadian energy systems supplier, and Green Park Management, a Nigerian energy and infrastructure firm

Element	Detail
Description	Oando operates diesel generation to compensate for poor grid reliability. Oando engaged Corvus Energy Africa Limited to install batteries and an integrated management system to reduce the volume, and increase the efficiency, of diesel generation at 13 Oando petrol stations.
Electricity market structure	Unbundled and partially privatised, but not liberalised at the retail level. Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. A substantial privatisation programme is underway in which the transmission element and some generation assets will remain state-owned but the bulk of Nigeria's generation assets and 11 distribution companies will be privatised.
Project status	Implementation commenced April 2014, expected completion 'mid 2014'
Project objectives	Expanding operating hours and reducing fuel use whilst maintaining reliability
Key technologies used and techniques applied	40 kWh capacity AT6500 lithium batteries at each petrol station; OutBack Radian inverters; integrated control system; existing diesel generators
Outcomes, barriers and successes	Technological: The use of battery technology not only reduces diesel generation through drawing power from the grid but also increases the efficiency of diesel generation by allowing it to operate an efficient level of load, with any excess power requirement being used to charge the batteries. In combination, these two effects allow for substantial reductions in diesel usage. The control system senses the availability of grid power and transitions to battery power in the event of a failure. When battery power becomes depleted, the generator starts automatically to power the petrol station loads and recharge the battery. Once the grid supply is restored the batteries are fully recharged if needed. Policy: No specific policy factors identified Economic: The Energy Storage Journal published analysis indicating that these applications could achieve payback in less than three years (Hampton, 2014). Corvus Energy claims fuel reductions of 50 to 80 per cent and an expansion of daily petrol station operating hours from 18 to 24.
Abatement outcomes	Not quantified, but fuel reductions are estimated at 50 to 80 per cent. The full volume of fuel use reductions will not represent abatement as some savings would be achieved by increased draw from the grid.
Key sources	(Corvus Energy, n.d.) (Allan, 2013) (Hampton, 2014)

Source: Vivid Economics and Arup

The five single user grid-connected mini-grid case studies cover a diverse range of end users and locations. Collectively the range of case studies highlights the potential for a range of relatively simple applications of distributed generation, battery storage and management systems to provide reliable power to users suffering from poor grid reliability.

In each case the project was privately funded by an organisation with high commercial or operational needs for reliable power. In all cases the user had previously met that need through use of diesel generation, and the projects involved replacing or augmenting that diesel use with renewable generation and/or batteries. The systems use proven, commercially available technologies and generally demonstrate strong economics. However, despite the use of decentralised technologies that could potentially contribute to wider network efficiency, the applications do not appear to be designed or intended to achieve this.

Case study descriptions for application #7: Grid-ready mini-grids

This section describes three case studies of grid-ready mini-grids in sequence.

Darewadi mini-grid

Table 21. **Case study #701: Darewadi mini-grid (Maharashtra, India)**

Element	Detail
Funding organisation	Bosch Solar Energy AG, a subsidiary of the German engineering company, covered the upfront capital costs through a corporate social responsibility programme.
Implementing organisation	Gram Oorja Solutions Private Limited, a private company specialising in commercialising rural renewable energy solutions
Description	Darewadi is village in the district of Pune with a population around 220 people. It has no grid connection. With upfront costs covered by Bosch, Gram Oorja installed a solar powered mini-grid with a peak capacity of 10 kW to serve Darewadi. The grid is maintained and managed by a local committee. 40 local households are connected and billed on a per unit basis. Use is measured through individual meters, with the proceeds covering the cost of battery replacement and grid maintenance. The mini-grid was designed to be 'grid-ready'.
Electricity market structure	Unbundled, but state-owned and not liberalised at the retail level. Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. No private participation except in the generation sector.
Project status	Completed in July 2012
Project objectives	To increase access to electricity, enabling productive uses of power and higher quality of life.
Key technologies used and techniques applied	10 kW solar PV system with batteries, inverters and a low voltage distribution network. Individual meters are installed for each connected household.

Element	Detail
Outcomes, barriers and successes	Technological: To achieve grid readiness, at design stage, it was decided that the mini-grid network would follow the wiring regulations of the Maharashtra's State Electricity Regulatory Board. This has driven the cost of installation up (compared to some easy cheap wiring solutions like using trees or not installing a suitable earthing network) but it has ensured that the safety of the users is not compromised and that the infrastructure can be readily connected to the grid once the extension arrives. The design further supports quality of power supply and grid readiness through separating the network into three feeders: households, street lights and commercial loads. This division enables the prioritisation of the loads at times of low power production, such as monsoon season. Policy: Regulation on interconnection within India is unclear, and poorly tailored to the mini-grid context. There are efforts ongoing to amend this, but the highly federalised political system creates barriers to simplifying the interconnection process. Economic: Electricity supplied through the grid is offered at a subsidised rate, which would undercut mini-grid supplied electricity if the grid was extended. Grid-readiness is therefore essential to ensure that, in the event of grid extension, the generation assets will still earn an income for the local community.
Abatement outcomes	Not quantified. Reduction of carbon emissions through use of solar power.
Key sources	(Fahey et al., 2014) (S. Deorah & Lath, n.d.) (S. M. Deorah, 2013)

Source: Vivid Economics and Arup

Darewadi is a strong illustration of the type of contexts in which interconnection should be built into mini-grid planning. The village is close to the grid; only one kilometre away from the nearest grid connected village. India provides a political and institutional context that makes future grid connection relatively likely, with consecutive governments targeting large increases in rural electrification through grid extension. Despite this, it remains uneconomical to extend the grid at the moment: extension costs are high due to hilly terrain; the load is small, with less than 50 households in the village, only small commercial loads from a flour mill and water pumping; and the local residents have strictly limited ability to pay.

The installation of a mini-grid therefore remains, over the short term, the best solution for improving electricity access. The combination of solar photovoltaics and batteries provides a minimal service of around six to seven kWh per household per month. This is sufficient to meet current household needs. Each household pays around 20 Rs per kWh of electricity consumed, which covers the costs of battery replacements and maintenance. Even with these low service levels, the electricity supply infrastructure would be unaffordable if the local villagers had to pay the capital costs of installation. These costs were instead fronted by Bosch as part of their corporate social responsibility.

Further, electricity consumption has been trending up since the installation of the grid. Once demand has matured through increased incomes and purchases of additional appliances, or through the emergence of an anchor customer such as a telecommunications tower, grid connection may be economically feasible. The general policy of 'grid-readiness' is more likely to offer benefits in the context of expected demand growth that would underpin future grid connection.

The case for making the mini-grid at Darewida 'grid-ready' is clear, but the process has been complicated by regulations on the interconnection process. The Indian Central Electricity Authority released a draft set of regulations in 2012 titled *Technical Standards for Connectivity of the Distributed Generation Resources* (Indian Central Electricity Authority, 2012), but these standards have not been developed to suit the particular issues around connecting mini-grids. This task has been set for the India Smart Grid Forum Working Group #9 who will make recommendations on both interconnection and tariff procedures. The latter point is of particular importance in the Indian context where heavily subsidised grid electricity, costing around 3 Rs per kWh, is likely to substantially undercut the generation costs of any micro-grid. This regulatory confusion is further complicated by the highly federalised nature of Indian electricity regulation and policy, much of which is determined by states. As it is, the Darewadi grid has been constructed to meet the wiring regulations of the Maharashtra's State Electricity Regulatory Board, but it is unclear exactly how interconnection would take place if the grid was extended to the village.

Athureliya community village

Table 22. **Case Study #702: Athureliya community village (Sri Lanka)**

Element	Detail
Funding organisation	The Sri Lanka Ministry of Environment and Renewable Energy
Implementing organisation	The Sri Lanka Ministry of Environment and Renewable Energy
Description	Athureliya is a village in Sri Lanka. Until 2010, electricity was provided through a small-scale hydro plant and mini-grid. After the national grid was extended to serve the village utilisation of the hydro plant was limited to a small number of households that could not afford grid connection. The hydro plant was retrofitted in 2012 to allow it to export electricity to the grid, underpinning the ongoing economic operation of the plant and generation of revenue for the village.
Electricity market structure	Largely vertically-integrated and state-owned. No liberalisation at the retail level. All elements of the supply chain integrated within the state-owned Ceylon Electricity Board, other than some distribution and retailing in limited areas through the private Lanka Electricity Company.
Project status	Completed in November 2012
Project objectives	Retrofitting the existing mini-grid in order to satisfy growing demand through grid connection, and allow export of excess power from the hydro plant when available
Key technologies used and techniques applied	22 kW mini hydro power plant, interconnection hardware

Element	Detail
Outcomes, barriers and successes	Technology: One of two approaches would have been involved in retrofitting of the hydro plant to serve the interconnected grid. The approach would have depended on the initial configuration of the hydro plant, which is not clear from the case study materials. One possibility is that the initial configuration was using an induction generation, which does not need to be synchronised to the grid. However, retrofitting for grid connection would have required 'soft starters' to limit the inrush currents and a capacitor bank to reduce the reactive power supplied by the grid. Alternatively the initial configuration would have been a synchronous generation, in which case an automatic synchronisation system would have been required to be installed. Policy: Grid interconnection standards have been developed by the Sustainable Energy Authority, which has simplified the interconnection process. The Athureliya hydro plant was the first to be connected under a Standardised Power Purchase Agreement aimed at encouraging interconnection for small generation assets. Economic: The costs of interconnection were approximately US$11,500, whereas revenues from the Standardized Power Purchase Agreement will be around US$7,700. The project should therefore pay-back in less than two years.
Abatement outcomes	Carbon reduction trough the local production and utilisation of power from hydro natural resources.
Key sources	(Greacen et al., 2013) (Sri Lanka Sustainable Energy Authority, 2011)

Source: Vivid Economics and Arup

Similarly to Darewadi village, Athureliya village is remote and consists primarily of households with limited ability to pay for electricity. Until 2010, local residents were served exclusively by a mini-grid and generation was provided by a 22 kW hydro plant. As part of a broader rural electrification scheme, the village was grid connected in 2010 and the hydro plant has now been connected to the central grid at the cost of approximately US$11,500. The 2012 retrofit of the hydro-plant allows it to provide electricity to the grid through a Standardized Power Purchase Agreement (SPPA), earning the village around US$7,700 per year.

The Athureliya example is likely to be representative of a range of other villages across Sri Lanka. An estimated 300 isolated villages in Sri Lanka are supplied by small hydro mini-grids, ranging from 3 to 55 kW in capacity. Grid connectivity has been drastically expanded over the past decade, to the point where 90 per cent of household now have access to grid electricity. As in Athureliya, many of the newly connected villages could benefit from interconnecting generation infrastructure to the central grid.

To enable this interconnection, the government introduced streamlined policies for small power producers. These policies apply to generators of less than 10 MW. The Sustainable Energy Authority has issued a guidebook laying out the steps for interconnection, which requires a pre-feasibility study, approval for developing a specific resource and the granting of an energy permit (Sri Lanka Sustainable Energy Authority, 2011). Plans are in development to connect some 100 additional village mini-grids to the main grid in a similar fashion to the Athureliya project, at an anticipated cost of US$1.5 million. The tariff offered has been tailored to change seasonally, with higher payments in dry seasons when hydropower is limited.

Streamlining the process does not reduce the infrastructure costs of interconnection but it does provide new build mini-grids with a roadmap to facilitate eventual grid connection. It also gives investors in mini-grids and generation assets greater long-term security, ensuring that in the event of grid extension their assets can still be profitably operated, rather than being displaced by subsidised grid electricity.

In Sri Lanka where a large number of mini-grids are already in operation, the technical aspects of grid connection such as synchronisation will have to be retrofitted at the time of connection. However, the Athureliya experience indicates how a streamlined process can clarify the commercial incentive to incur these retrofit costs and support timely retrofitting.

Sagar island mini-grid

Table 23. **Case Study #703: Sagar Island (West Bengal, India)**

Element	Detail
Funding organisation	Grid connection was funded by the Indian national rural electrification program, Rajiv Gandhi Gramin Vidyutikaran Yojna (RGGVY), and the World Bank
Implementing organisation	West Bengal Green Energy Development Agency (WBGEDA) implemented the initial mini-grid based electrification; West Bengal State Electricity Distribution Company Limited (WBSEDCL) implemented the extension of the national grid
Description	Between 2000 and 2004, around 1 MW of solar and wind/diesel hybrid generation capacity was constructed on Sagar Island, serving 2,000 households. Since 2009, RGGVY has been rolled out to connect the area to the national grid. The scheme does not take into account local existing mini-grids. The former mini-grid assets have been largely discarded as the grid has been expanded to the island.
Electricity market structure	Unbundled, but state-owned and not liberalised at the retail level. Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. No private participation except in the generation sector.
Project status	The former mini-grid assets are dis-used.
Project objectives	Connection of Sagar Island to the central grid, supporting increased productive use of electricity on the island and reduced electricity tariffs for residential consumers.
Key technologies used and techniques applied	Traditional grid-interconnection design

Element	Detail
Outcomes, barriers and successes	Technological: There is limited information available on the technical barriers that have potentially prevented interconnection of existing assets. The primary barriers appear to have been policy and economic rather than technical. Policy: Interconnection is complicated by the lack of simple guidelines for the interconnection process or standardised small power purchasing agreements. Economic: Although the existing mini-grids would be unable to compete with subsidised grid tariffs on a total cost basis, the opportunity cost of neglecting low marginal cost (renewable) generation assets is potentially significant. In the absence of a clear opportunity to sell power via the main grid, incentives to continue the operation of the pre-existing equipment may have been insufficient, leading to their neglect.
Abatement outcomes	Not applicable
Key sources	(Shrank, 2008) (Mondal & Mandal, 2013) (West Bengal State Electricity Distribution Company, n.d.)

Source: Vivid Economics and Arup

The Sagar Island case study demonstrates the potential costs that can be incurred when mini-grids are not designed as 'grid-ready'. In contrast to the experience in Darewadi and Athureliya villages, the mini-grid infrastructure constructed on Sagar Island has been largely discarded as the grid has expanded.

Starting from 1996, a number of mini-grid and small generation facilities were constructed on Sagar Island. This includes 10 solar stations with capacity between 20 kW and 120 kW and a single wind-diesel hybrid plant. Jointly, these facilities have a capacity of over 1 MW, serving around 2,300 households. Individual solar panels are also widespread, with around 5,000 households having access to some form of solar home system (Shrank, 2008).

Almost all of this infrastructure is being discarded in the recent push to connect the island to the central grid. Under the auspices of the Rajiv Gandhi Gramin Vidyutikaran Yojna (RGGVY) programme of electrification, the required infrastructure has been under construction since 2010 and includes a high voltage line across the estuary and low voltage lines and transformers throughout the island. Sagar Island is being connected as part of a project to connect the Indian Sundarbans funded by the West Bengal state government and RGGVY, providing electricity to around 350,000 households.

It is unclear why the existing infrastructure is not being used. The drive for connection to the central grid seems to be due, in part, to the supposition that rapid population growth would lead to increases in electricity demand and population density that could only be efficiently met through grid connection. The official program documents do not mention the use of solar or wind power in Sagar Island, claiming that all existing electricity demand is met by six diesel generating sets on the island (West Bengal State Electricity Distribution Company, n.d.). Potentially, the existing infrastructure is not functioning at a reasonable level; independent analysis of the programme conducted in 2008 questioned the sustainability of the management systems for the solar mini-grids, raising doubts as to whether they would be able to raise sufficient revenue for maintenance. The lack of clear regulation on interconnection, discussed in the Darewadi case study, may also play a role.

Case study descriptions for application #12: Smart metering and ICT to address non-technical losses

This section describes three cases studies of approaches addressing non-technical losses in sequence.

Ampla power theft program

Table 24. **Case study #1201: Ampla power theft program (Rio de Janeiro, Brazil)**

Element	Detail
Funding organisation	Ampla Energia and Servicos S.A. (Ampla), the electricity distribution network operator which provides electricity to 73% of the state of Rio de Janeiro.
Implementing organisation	Ampla; Landis and Gyr (metering)
Description	Ampla rolled out a series of smart meters to reduce power theft and assist metering and billing in dangerous slum areas of Rio de Janeiro. Ampla built a distribution network where medium voltage and low voltage are located on the same pole and each individual customer is directly connected from a medium to low voltage pole mounted transformer. Smart meters were located in secure boxes at the top of distribution poles rather than at the customer premises, reducing the risk of meter tampering. Each customer was connected to the meter box by a dedicated circuit, which itself was directly connected to the medium voltage network to reduce opportunities for theft from the low voltage network. The meter communicates consumption data remotely to the utility, allowing billing and consumption data to be handled via mobile phones or in home displays. As well as reducing operating costs, this approach reduces safety risks to billing staff entering slum areas.
Electricity market structure	Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. Some private participation in the generation sector, and limited elsewhere.
Project status	Roll out started in 2003; by December 2007 380,000 customers had remote meters installed
Project objectives	The key objectives of the project are to reduce power theft, reduce metering and billing costs and improve the safety of utility employees.
Key technologies used and techniques applied	Smart meters, remote data telemetry, innovative distribution network design

Element	Detail
Outcomes, barriers and successes	Technological: Prior to the project Ampla incurred average losses of 23.6 per cent, reaching up to 52 per cent in some areas. Between 2003 and 2006 non-technical losses were reduced by 30 per cent (Carvalho et al., 2014). Ampla further claims that non-technical losses are effectively eliminated wherever the programme is rolled out (World Bank 2011). This experience indicates that metering and innovative distribution network design solutions successfully addressed power theft in this case study. Policy: Power theft was associated with the lack of access to personal banking and corruption of the commercial team responsible for bills collection. The use of technology reduced the opportunity for fraud amongst company employees. The initial change in metering systems produced significant customer backlash. Ampla responded with a substantial programme of social development initiatives to improve energy efficiency, reduce power costs for newly compliant customers and improve relationships with customers (Carvalho et al., 2014). Economic: The program attracted US$212 million of financing from Brazilian Development Bank BNDES. The Brazilian energy regulator recognises that the despite the high costs of the approach it is the lowest cost approach to reducing non-technical losses in applicable areas. Smart meter installations at larger commercial premises can achieve a payback period of less than one year (World Bank Energy Unit, 2011)
Abatement outcomes	Effects of the scheme on electricity consumption and emissions have not been documented
Key sources	(Carvalho et al., 2014) (Accenture & CISCO, n.d.) (Antmann, 2009) (World Bank Energy Unit, 2011) (World Bank Group, 2012)

Source: *Vivid Economics and Arup*

Ampla's introduction of smart meters indicates both the high potential of effective loss reduction schemes and the necessity of applying the technology as part of a broader, integrated approach. In 2003, Ampla reported non-technical losses for some parts of their concession area exceeding 50 per cent. Losses of this magnitude drastically impair the ability of the utility to make any return on an investment in improved supply. Ampla had losses of 23 to 25 per cent for Rio de Janeiro as a whole.

Smart meters can form one element of an effective response to this issue. By locating meters within sealed concentrator boxes on the top of electricity posts and utilising remote data telemetry, Ampla could almost guarantee that they received accurate data on usage. The smart metering system and inaccessible location of the meter removes the opportunity to tamper with equipment and the incentive for meter readers and electricity users to collude to reduce billed consumption. Through linking them to commercial information systems, smart metering can be used to automatically read, connect and disconnect consumers.

Theft prevention was supported by a range of changes to the design of the distribution network. These include increasing pole height and the distance of low voltage wires from poles, and locating medium voltage and low voltage lines close together. A key change was supplying each customer via a direct feed from a pole mounted transformer. By locating meters on the top of electricity poles at the point of connection to the medium-voltage network, illegally connecting to the low voltage network is made more difficult and dangerous due to the limited amount of low voltage wiring. Further, theft from the low voltage wires would be ‘behind’ the meter and so be at the expense of the customer rather than the wider network.

However, while the smart metering system appears to have been immediately successful in reducing losses, it initially faced significant backlash. Bills for many households increased significantly and, in some cases, unexpectedly. There were many cases of legal action against Ampla; at its peak, there were 447 lawsuits and court processes linked with the smart meters during one month in 2007 (Carvalho et al., 2014). Tensions emerged between the company and local politicians.

Technological responses to non-technical losses need to be implemented alongside measures to overcome social and political barriers. For instance, there is evidence in other contexts of a strong correlation between electricity theft and electoral cycles, with greater theft occurring nearer to polling dates (Min & Golden, 2014). While there is no evidence for this within Rio de Janeiro, it indicates the importance of understanding the broader institutional factors that result in high theft; the problem is not purely technical.

Ampla have dealt with the backlash through implementing a broad set of social development initiatives (Carvalho et al., 2014). These include:
- education campaigns to encourage more efficient energy use;
- replacement of old appliances with more efficient alternatives;
- recycling programmes, with consumers offered rebates on their bills in exchange for materials;
- capacity building on energy consumption for professors and students at public schools; and
- capacity building for young adults finding their first job.

There has recently been a decline in legal action related to the smart metering and the backlash appears to be more limited. It is plausible, though ultimately unclear, that this is partly due to increased emphasis on the social aspects of electricity theft.

Smart metering and ICT in North Delhi

Table 25. **Case study #1202: Smart metering and ICT in North Delhi (India)**

Element	Detail
Funding organisation	Tata Power Delhi Distribution Limited (TPDDL), a joint venture between Tata Power (51 per cent) and the Government of Delhi (49 percent). TPDDL distributes electricity in north and northwest Delhi and has a registered customer base of about 1 million. TPDDL was formerly known as North Delhi Power Limited.
Implementing organisation	TPDDL

Element	Detail
Description	To tackle the issue of electricity theft (non-technical losses) in north and northwest Delhi, TPDDL installed smart meters and associated ICT systems such as customer billing databases.
Electricity market structure	Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. Private participation in the generation sector, and at the distribution/retailing level through TPDDL.
Project status	The initiative commenced in 2002 soon after TPDDL was formed and continued after a review in 2008
Project objectives	To reduce non-technical losses, reduce lost revenue and improve profitability. This would further allow improved customer service.
Key technologies used and techniques applied	Advanced metering infrastructure (AMI) was installed for all consumers with demand of 15 kW and above. Medium voltage distribution lines were extended into theft-prone areas and customers were connected directly from the medium voltage network. A complaints forum allowed people to anonymously report theft. Collaboration with non-governmental organizations improved awareness about the dangers of tapping electricity wires.
Outcomes, barriers and successes	Technological: TPDDL achieved a dramatic reduction in non-technical losses over six years, moving from 53% at takeover in July 2002 to 15% by April 2009 (World Bank 2011). Policy: Reduction of losses has allowed TPDDL to consistently operate below the regulator set target for total losses. TPDDL was able to keep a share of the profits that resulted from exceeding this target, creating strong incentives to reduce losses. This incentive regime appears important to supporting TPDDL’s programme. Economic: TPDDL identified that it was most cost effective to target non-technical losses among large consumers, as consumers of 15 kW or above represent only 2.7 per cent of customer numbers but account for almost 60 per cent of revenue (World Bank 2011)
Abatement outcomes	Not documented
Key sources	(Antmann, 2009) (World Bank Energy Unit, 2011)

Source: Vivid Economics and Arup

In the case of Tata Power smart metering was deployed primarily to tackle electricity theft by high volume consumers. Most of these users were industrial or commercial, and relied on collusion with meter reading staff to reduce electricity bills. Jointly, consumers with a demand greater than 15 kilowatts represented only three per cent of total users but contributed almost 60 per cent of revenue.

There are several advantages to this approach. First, given the relatively high cost of smart meters, focusing on high volume users offers good value for money. One meter can be installed for each user, which makes attribution of theft less problematic, and the resulting reductions in electricity theft are likely to have a large impact on total revenues. Second, focusing on high volume consumers may minimise the potential for social backlash. There is little evidence of significant legal or political action against TPDDL following the introduction of smart metering. Third, strong action against a subset of consumers could potentially have broader knock-on effects by changing the norms surrounding payment for electricity.

When the drive to reduce non-technical losses extended to residential consumers, smart metering formed a smaller component of the overall strategy. Technical measures were combined with community programmes to increase billing transparency, improve awareness of the dangers of illegal wire-tapping and increase availability of support for households. As in the Ampla example, small customer theft was also addressed by redesigning the low voltage distribution network to increase the difficulty of tapping wires. Principally this involved replacing low voltage distribution lines with medium voltage lines. Small transformers were positioned near load sites to step down the voltage at the point of connection for each consumer. Where low voltage lines were exposed, the traditional bare cables were replaced with insulated aerial-bunched cables which are better protected from weather related damage and electricity theft. By contrast, leadership within TPDDL estimated that advanced metering infrastructure among high-volume users was the primary driving force in non-technical loss reduction (World Bank Energy Unit, 2011).

This case study also demonstrates the important role of incentives. The regulator sets targets each year for technical and non-technical losses, with the target decreasing to reflect improvements in distribution and billing. TPDDL is allowed to keep revenues from electricity that is billed over and above the target set for the year. By consistently outperforming the target, TPDDL has increased annual profits. This ensures that the distributor has a positive incentive to decrease non-technical losses, and that the institutional incentives are aligned with the broader interests of the electricity sector.

Edesur anti-theft program

Table 26. **Case study #1203: Edesur anti-theft program (Dominican Republic)**

Element	Detail
Funding organisation	Edesur, a state-owned electricity distributor serving around 400,000 customers in and around the capital city Santo Domingo; indirect assistance from sector turn-around loan package from the World Bank with the potential to disburse up to $150 million.
Implementing organisation	Edesur

Element	Detail
Description	As a key part of a broader electricity sector package supported by a World Bank loan, Edesur installed AMI infrastructure to target non-technical losses from 7,400 large industrial and commercial premises and 18,100 low voltage customers. Total investment was US$7.2 million. The use of AMI was supported by anti-theft legislation passed by the Government of the Dominican Republic in August 2007.
Electricity market structure	Generation, transmission and distribution are unbundled, with distribution and retailing functions remaining bundled within various power distribution companies with geographic monopolies. Full or part privatisation of each element of the supply chain occurred in 2001, with the distribution component partly renationalised in 2003.
Project status	Implemented between 2005 and 2008
Project objectives	To improve the commercial viability of the company to improve services and expand access, especially to the urban poor
Key technologies used and techniques applied	AMI located at distribution sub-stations with remote communication of consumption data
Outcomes, barriers and successes	Technological: Loss reductions were clear but modest, declining from 38.8 per cent in 2005 to 31.9 per cent in 2008. The World Bank identified that the measures adopted had particularly improved the ability of distribution companies to reduce theft by large customers (World Bank Caribbean Country Unit, 2009). The high stabilised level of losses may be related to the scope of the program or difficulties with the remote communication technology, which resulted in some reversions to direct bill reading. Policy: The rationale for World Bank investment in this sector was in part based on the fact that tackling power theft by both large and influential customers, and by particularly poor consumers with illegal connections, is politically difficult, and therefore that external financial incentives were needed to motivate the programme. Economic: The World Bank estimates that the payback period for the AMI theft program was only 3.5 years (World Bank Energy Unit, 2011), indicating robust economics. Further investment in anti-theft measures may have been limited by increases in oil prices, which weakened the finances of Edesur despite measures to reduce losses.
Abatement outcomes	Not documented
Key sources	(AES Dominicana, 2004) (World Bank Caribbean Country Unit, 2009) (World Bank Energy Unit, 2011)

Source: *Vivid Economics and Arup*

Electricity service levels in the Dominican Republic are extremely poor. Less than 50 per cent of customers are supplied for 24 hours a day. Shortages were, and continue to be, frequent – 20 per cent of the businesses in the World Bank Enterprise survey identified unreliable electricity supply as their biggest obstacle, with an average of 18 outages per month. These problems are greatly exacerbated by the substantial losses that are incurred through distribution. In 2005, only 54 per cent of the power purchased by distributors was eventually paid for by customers.

As in North Delhi, advanced metering infrastructure was targeted initially at high volume industrial and commercial consumers. The installation of advanced metering infrastructure initially reduced losses and improved cash recovery; non-technical losses declined quickly from 38 per cent in 2005 to 32 per cent by 2008. However, these numbers are likely to overstate the effect of the smart meters themselves and there is some evidence that the programme underperformed in several key technical dimensions.

The effect of smart meters may be overstated due to the coordination of their installation with broader changes. An electricity sector program was the basis for a World Bank loan, with disbursement tied to various policy changes, government actions and improvements in quantitative metrics. One of the criteria for disbursement was improvements in a defined ‘Cash Recovery Index’ (power paid for by customers divided by power purchased by distributors). Many of the other incentivised policy changes would have directly supported reduced non-technical losses, such as the requirement for the government to remain current on their electricity bills. Electricity theft was also made illegal in August 2007, with stringent penalties imposed on thieves. Any or all of these changes may have played a significant role in the observed reduction in non-technical losses, and the direct incentivisation of improvements in the Cash Recovery Index may have driven a range of unobserved changes in systems and governance within the utility and distributors.

This is particularly plausible given the limitations in the advanced metering roll-out. The World Bank reports that the internal implementation did not incorporate meter data management software (World Bank Energy Unit, 2011). Systems of this kind are required to detect abnormal situations indicating theft. In addition, 2,500 largest medium and high voltage consumers were monitored through indirect meter readings involving algebraic calculation of consumption given known total local grid supply and other loads on network. To avoid overloading the telemetry network, data is only transmitted above certain scales of consumption (for example 1,000 kWh equivalent to 1 unit). As not all data was being transmitted, the accuracy of billing was compromised and a costly return to manual meter reading was required for a period (World Bank Energy Unit, 2011).

Again, this programme illustrates the importance of recognising political constraints in the electricity market, even when considering applications that appear highly technical in nature. The historically poor quality of service in the Dominican Republic and the widespread perception of poor governance have led to deep politicisation of electricity issues. Electricity sector institutions can appear to be weak – for instance, the remote transmission of metering information for high voltage consumers could, technically, have been fixed by the relatively low cost installation of modems, but this did not happen. The performance of Edesur and policy-makers in relation to the broader World Bank programme was rated by the bank as ‘unsatisfactory’. Particular blame was laid on the lack of political will to update retail tariffs to be cost-reflective or adopt tariff structures that automatically adjusted with exchange rates, the price of oil and inflation.

Appendix C: Literature review bibliography

The findings discussed in Table 4 are based on a review of the academic and grey literature covering each of the six main network technologies and techniques. The purpose of this review was not to exhaustively cover all available literature, but rather to collate sufficient high quality sources to determine whether each potential area was likely to be high priority. Table 27 collects the references used. It is organised by technology, due to the high level of cross-over from sources between different user-contexts.

Table 27. **Literature drawn upon through the broad literature review**

Technology or technique	Main references
Network assets	Asian Development Bank. 2014. *Bangladesh-India Electrical Grid Interconnection Project, Project Data Sheet*. DESA. 2006. *Multi Dimensional Issues in International Electric Power Grid Interconnections*. East-West Center. 2005. *Electric Power Grid Interconnection in Northeast Asia*. GIZ. 2011. *Grid Extension in Countries of Power Shortages: Experience from Energising Development*. IEA. 2010. *Comparative Study on Rural Electrification Policies in Emerging Economies*. Poch, Kongchheng, and Savong Tuy. 2012. *Cambodia's Electricty Sector in the Context of Regional Electricity Market Integration*. World Bank. 2010. *Addressing the Electricity Access Gap*.
Generation assets	Business Council for Sustainable Energy. 2004. *Increasing Energy Access in Developing Countries: The Role of Distributed Generation*. Camco, UNDP, and Climate Parliament. 2010. *Mini-grid Toolkit Field Study Report for Kenya, Mozambique and Zambia*. Casten, Thomas, and Brennan Downes. 2005. "Critical Thinking About Energy: The Case for Decentralized Generation of Electricity." Deshmukh, Ranjit, Juan Pablo Carvallo, and Ashwin Gambhir. 2013. *Sustainable Development of Renewable Energy Mini-grids for Energy Access: A Framework for Policy Design*. ESMAP. 2007. "Technical and Economic Assessment of Off-grid, Mini-grid and Grid Electrification Technologies." *Technical Paper 121/07* (December). European Parliament. 2010. *Decentralised Energy Systems*. Greacen, Chris, Richard Engel, and Thomas Quetchenbach. 2013. *A Guidebook on Grid Interconnection and Islanded Operation of Mini-Grid Power Systems Up to 200 kW*. GVEP International. 2011. *The History of Mini-grid Development in Developing Countries*. Harper, Meg. 2013. *Review of Strategies and Technologies for Demand-Side*

Technology or technique	Main references
	Management on Isolated Mini-Grids. Innovation Energie Developpement. 2013. *Identifying the Gaps and Building the Evidence Base on Low Carbon Mini-grids*. Owens, Brandon. 2014. *The Rise of Distributed Power*. Pecas Lopes, J.A., N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins. 2010. “Integrating Distributed Generation into Electric Power Systems: A Review of Drivers , Challenges and Opportunities.” *Electric Power Systems Research* 77 (2007): 1189–1203 Probe International. 2009. *Powering 21st Century Cambodia with Decentralized Generation*. Tenenbaum, Bernard, Chris Greacen, Tilak Siyambalapitiya, and James Knuckles. 2014. *From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa*. Thirumurthy, N, L Harrington, D Martin, L Thomas, Nisha Thirumurthy, and Laura Harrington. 2012. *Opportunities and Challenges for Solar Minigrid Development in Rural India Opportunities and Challenges for Solar Minigrid Development in Rural India*.
Storage	APS Physics. 2007. *Challenges of Electricity Storage Technologies*. Eurelectric. 2012. *Decentralised Storage: Impact on Future Distribution Grids*. Fuchs, Georg, Benedikt Lunz, Matthias Leuthold, and Dirk Uwe Sauer. 2012. *Technology Overview on Electricity Storage*. Hittinger, Eric, J.F. Whitacre, and Jay Apt. 2012. “What Properties of Grid Energy Storage Are Most Valuable?” *Journal of Power Sources* 206 (May): 436–449. IEA. 2014. *Technology Roadmap: Energy Storage*. IEA-ETSAP, and IRENA. 2012. *Electricity Storage: Technology Brief*. IEC. 2011. *Electrical Energy Storage*. Ramchurn, Sarvapali D, Perukrishnen Vytelingum, Alex Rogers, and Nick Jennings. 2011. *Agent-Based Control for Decentralised Demand Side Management in the Smart Grid*.
Smart meters and other smart ICT devices	Amin, Massoud. 2013. *The self-healing grid: a concept two decades in the making.* Antmann, Pedro. 2009. “Reducing Technical and Non-Technical Losses in the Power Sector.” *Background Paper for the World Bank Group Energy Sector Strategy*. Bhatia, Bhavna, and Mohinder Gulati. 1998. “Reforming the Power Sector: Controlling Electricity Theft and Improving Revenue.” *World Bank Public Policy for the Private Sector Note Number 272*. EY. 2013. *Smart Metering — Transforming Africa’s Energy Future*. Rámila, Pablo, and Hugh Rudnick. 2010. *Assessment of the Introduction of Smart Metering in a Developing Country*. Sastry, Chellury, Pratt, Rob, Srivastava, Viraj and Shun Li. 2010. Use of residential smart appliances for peak-load shifting and spinning reserves: cost-benefit analysis. Shekara, Soma, Sreenadh Reddy, Lingfeng Wang, Vijay Devabhaktuni, and Nikhil Gudi. 2011. *Smart Meters for Power Grid – Challenges, Issues, Advantages and Status*.

Technology or technique	Main references
Operation, maintenance and planning	Auriol, Emmanuelle, and Pierre M Picard. 2006. "Infrastructure and Public Utilities Privatization in Developing Countries" 32 (10): 1–42. Besant-Jones, John E. 2006. "Reforming Power Markets in Developing Countries: What Have We Learned?" *Energy and Mining Sector Board Discussion Paper No. 19*. Bhatia, Bhavna, and Mohinder Gulati. 1998. "Reforming the Power Sector: Controlling Electricity Theft and Improving Revenue." *World Bank Public Policy for the Private Sector Note Number 272*. Gabriele, Alberto. 2004. "Policy Alternatives in Reforming Power Utilities in Developing Countries: A Critical Survey." *United Nations Conference on Trade and Development Discussion Paper No. 168*. Irwin, Timothy, and Chiaki Yamamoto. 2004. "Some Options for Improving the Governance of State-Owned Electricity Utilities." *Energy and Mining Sector Board Discussion Paper No. 11*. Sutton, Christopher. 2007. *The Role of the Utilities Sector in Expanding Economic Opportunity*. Tallapragada V.S.N., Prasad, Maria Shkaratan, Ada Karina Izaguirre, Jaakko Helleranta, Saifur Rahman, and Sten Bergman. 2009. *Monitoring Performance of Electric Utilities: Indicators and Benchmarking in Sub-Saharan Africa*.
Smart Grids	International Renewable Energy Agency IRENA "*Smart Grids and Renewables – A guide for effective deployment*", November, 2013. Welsch Manuel et al. "*Smart and Just Grids for sub-Saharan Africa: exploring options*", Renewable and Sustainable Energy Reviews, vol. 20, pp. 336-352, 2013. Bollen Matt H. "*Understanding power quality problems: voltage sags and interruptions*", IEEE Press Series on Power Engineering, New York, 2000.
Mini-grids and rural electrification	Bello Mobolaji, Smit Riaan, Carter-Brown Clinton and Davidson Innocent E. "*Power planning for renewable energy grid integration – Case study of south Africa*", Power and Energy Society General Meeting (PES), 2013 IEEE. Cronje W.A. et al. "*Design considerations for rural modular microgrids*", 2nd IEEE ENERGYCON Conference & Exhibition, 2012. Greacen Chris, Engel Richard and Quetchenbach "*A guidebook on grid interconnection and islanded operation of mini-grid power systems up to 200 kW*", Lawrence Berkeley National Laboratory and Schatz Energy Research Centre , April 2013. Joint UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP), "*Reducing the cost of grid extension for rural electrification*", February 2000. Lasseter Bob et al., "*Integration of distributed energy resources: The certs microgrid concept*," Consortium for Electric Reliability Technology Solutions, April 2002. Rahman Md. Mizanur, Paatero Jukka V. and Lahdelma Risto "*Evaluation of choices for sustainable rural electrification in developing countries: a multicriteria approach*", Energy Policy, Vol. 59, pp. 589-599, 2013. Zomers, Adrian "*Remote access*", IEEE Power & Energy Magazine, Vol. 12, No. 4, July/August 2014.

Source: Vivid Economics and Arup

Appendix D: References

Accenture, & CISCO. (n.d.). *Smart Mobile Cities: Opportunities for Mobile Operators to Deliver Intelligent Cities*.

AES Dominicana. (2004). *Sustainable Development of the Dominican Electrical Sector*.

Allan, G. (2013). Advanced energy storage as a key to global sustainability. In *World Future Energy Summit*. Abu Dhabi.

Alliance for Rural Electrification. (n.d.). *Best practices of the Alliance for Rural Electrification*.

Alliance for Rural Electrification. (2013). *Using batteries to ensure clean, reliable and affordable universal electricity access*.

Antmann, P. (2009). *Reducing Technical and Non-Technical Losses in the Power Sector*.

Apple, J., Vicente, R., Yarberry, a., Lohse, N., Mills, E., Jacobson, a., & Poppendieck, D. (2010). Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. *Indoor Air*, *20*(5), 399–411. doi:10.1111/j.1600-0668.2010.00664.x

Bjelovuk, G. (2010). American Electric Power's Utility-Scale Energy Storage.

Carvalho, L., Germini, M., van den Berg, L., & van Tuijl, E. (2014). *Energy transitions in cities: Rio de Janeiro case study*.

Centre for Development Finance. (n.d.). *Empowering Villages: A comparative analysis of DESI Power and Husk Power Systems*.

Clean Development Mechanism Executive Board. (2006). *PROJECT DESIGN DOCUMENT FORM (CDM-SSC-PDD) - Version 03: Mwenga Hydro Power Project* (pp. 1–71).

Corvus Energy. (n.d.). Case Study: Oando Petrol Station.

Deorah, S., & Lath, A. (n.d.). Electricity access in rural India using solar PV mini-grids.

Deorah, S. M. (2013). Prospects for provision of Electricity beyond Lighting in Rural India.

Fahey, A., Freymiller, H. S., Li, S., Huang, C., Moilanen, S., Onda, C., … Wong, J. (2014). *Rural Energy Alternatives in India: Opportunities in Financing and Community Engagement for Renewable Energy Microgrid Projects*.

Fischmann, J. (2013). PV-Diesel-Hybrid Systems for Industrial Applications.

Garcia, R. (2013). High Quality Lead-Acid Batteries supporting reliabilty of Solar Powered Backup for ATMs in Nigeria.

Gratwicke, M. (2013). Small Hydro Development in Tanzania. In *ESMAP Knowledge Exchange Forum*. The Hague.

Greacen, C., Engel, R., & Quetchenbach, T. (2013). *A Guidebook on Grid Interconnection and Islanded Operation of Mini-Grid Power Systems Up to 200 kW*.

GSMA. (2014). *Tower Power Africa : Energy Challenges and Opportunities for the Mobile Industry in Africa*.

Hampton, K. (2014). *A little power in the hands of many*. *Energy Storage Journal*. Retrieved from http://www.energystoragejournal.com/a-little-power-in-the-hands-of-many/

IEA, UNDP, & UNIDO. (2010). *Energy Poverty: How to make modern energy access universal?*.

Imergy Power Systems. (n.d.). Energy savings using flow batteries: telecom base station application, 1–16.

Indian Central Electricity Authority. Draft Technical Standards for Connectivity of the Distributed Generation Resources (2012).

Jhunjhunwala, A., Ramamurthi, B., Narayanamurthy, S., Rangarajan, J., & Raj, S. (n.d.). *Powering cellular base stations: a quantitative analysis of energy options*.

Lighting Africa. (2014). Energy and Carbon Benefits of Pico-powered Lighting. *Eco Design Notes: Issue 4*.

Macleman, D. (n.d.). The Orkney Smart Grid.

Min, B., & Golden, M. (2014). Electoral cycles in electricity losses in India. *Energy Policy*, *65*, 619–625.

Mondal, M., & Mandal, S. (2013). *Remote Village Electrification through Renewable Solar energy: a Case Study of Sagar Island* (pp. 201–205).

Nourai, A. (2007). *Installation of the First Distributed Energy Storage System at American Electric Power: A Study for the DOE Energy Storage Systems Program*.

Nourai, A. (2009). Energy Storage Projects in AEP: a migratory trend (pp. 1–17).

Nourai, A., & Kearns, D. (2010). Batteries Included: Realizing Smart Grid Goals with Intelligent Energy Storage. *IEE Power and Energy Magazine*, 49–54.

Offgrid Energy. (n.d.). Power solution for Haiti Hospital Appeal.

S&C Electric Company. (2014). Canada' s First Utility-Scale Energy Storage System Islands Remote Town During Outages.

Schnitzer, D., Lounsbury, D. S., Carvallo, J. P., Deshmukh, R., Apt, J., & Kammen, D. (2014). *Microgrids for Rural Electrification : A critical review of best practices based on seven case studies Microgrids for Rural Electrification : A critical review of best practices*.

SE4ALL. (2013). *Global Tracking Framework*.

Seetharam, D. P., Agrawal, A., Ganu, T., Hazra, J., Rajaraman, V., & Kunnath, R. (2013). *Hidden costs of power cuts and battery backups*. *Proceedings of the the fourth international conference on Future energy systems - e-Energy '13* (p. 39). New York, New York, USA: ACM Press. doi:10.1145/2487166.2487171

Shrank, S. (2008). *Another Look at Renewables on India's Sagar Island*.

SMA Solar Technology. (n.d.). Hybrid Energy Supply for A Cotton Mill: SMA Fuel Save Solution for Photovoltaic Diesel Hybrid Systems.

Smarter Grid Solutions. (n.d.). Orkney Smart Grid case study. Retrieved from http://www.smartergridsolutions.com/media/32731/sgs-case-study-orkney-final.pdf

Southern Energy Power Distribution. (2013). *Innovation Funding Incentive and Registered Power Zone Report Southern Electric Power Distribution*.

Sri Lanka Sustainable Energy Authority. (2011). *On-grid renewable energy development: a guide to the project approval process* (pp. 0–51).

Tenenbaum, B., Greacen, C., Siyambalapitiya, T., & Knuckles, J. (2014). *From the Bottom Up: how small power producers and mini-grids can deliver electrification and renewable energy in Africa*.

Trojan Battery Company. (n.d.). Diamond Bank's Solar-Powered ATMs Case Study. Retrieved from http://www.trojanbattery.com/pdf/RE_CS_Eauxwell.pdf

Victron Energy. (n.d.). Off-grid back-up and island systems.

Vivid Economics. (2013). *Delivery vehicle options for the International Climate Fund*.

Wartsila. (2009). *The real cost of power* (Vol. 45). doi:10.2307/4611806

Weaver, T. (2014). American Electric Power Energy Storage Presentation to IEEE, DOE and EAC. In *Energy Storage June 2014* (pp. 1–17).

West Bengal State Electricity Distribution Company. (n.d.). *100 per cent household electrification of Sagar Island: detailed project report*.

World Bank. (2014). *Enterprise Surveys*.

World Bank Caribbean Country Unit. (2009). *Implementation and completion and results report: Dominican Republic programmatic power sector reform loan*.

World Bank Energy Unit. (2011). *Applications of Advanced Metering Infrastructure in Electricity Distribution Draft Report*.

World Bank Group. (2012). *From Gap to Opportunity: Business Models for Scaling Up Energy Access*.

Xero Energy. (2014). *Scottish Islands Renewable Project: Grid Access Study*.

Contact us:

Vivid Economics Limited
The Media Village
131-151 Great Titchfield Street
London W1W 5BB
United Kingdom

T: +44 (0)844 8000 254
E: enquiries@vivideconomics.com

Company Profile

Vivid Economics is a leading strategic economics consultancy with global reach. We strive to create lasting value for our clients, both in government and the private sector, and for society at large.

We are a premier consultant in the policy-commerce interface and resource- and environment-intensive sectors, where we advise on the most critical and complex policy and commercial questions facing clients around the world. The success we bring to our clients reflects a strong partnership culture, solid foundation of skills and analytical assets, and close cooperation with a large network of contacts across key organisations.