Computer-aided electrification planning in developing countries: The Reference Electrification Model (REM)

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Authors (in alphabetical order):

Amatya, Reja ; **Barbar**, Marc ; **Borofsky**, Yael ; **Brusnahan**, Matt ; **Ciller**, Pedro ; **Cotterman**, Turner ; **de Cuadra**, Fernando ; **Drouin**, Cailinn ; **Dueñas**, Pablo ; **Ellman**, Douglas ; **González-García**, Andrés ; **Lee**, Stephen ; **Li**, Vivian ; **Mateo**, Carlos ; **Oladeji**, Olamide ; **Palacios**, Rafael ; **Pérez-Arriaga**, Ignacio ; **Stoner**, Robert ; **Vergara**, Claudio.

Abstract.

In many parts of the world, access to basic electricity services remains a significant challenge. The status quo mode of electrification is central grid extension; however, in many areas off-grid technologies like mini-grids and stand-alone systems are more suitable for promoting electricity access under cost constraints. Unfortunately, these opportunities are often overlooked due to the complexities of electrification planning, especially for large areas.

Researchers have designed techno-economic planning tools that can be scaled to cut through aspects of this complexity and be fit to address different places and contexts. This working paper describes a computer-based optimization tool that performs automatic electrification planning and is able to identify lowest cost system designs to most effectively provide desired levels of electricity access to populations of any given size. In doing so, the model determines the most suitable modes of electrification for each individual consumer. Concretely, this represents specifying whether customers should be electrified via grid extension, off-grid mini-grids, or stand-alone systems. For each system, the model supplies detailed technical designs at the individual customer-level.

This software tool – named the Reference Electrification Model (REM) – has been used in real planning activities in sub-Saharan Africa and South Asia. The description of the capabilities of the model is supported by case examples. REM stands apart from other planning tools because of its high granularity and its capability to provide concrete plans for a wide range of geographical scales. Because of these benefits, REM has the potential to help rationalize electrification planning and expedite progress towards universal electricity access worldwide.

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1. Introduction.

The lack of electricity access for populations in many low-income and developing countries is a major contemporary issue, with complex social, ethical, environmental, economic, and technical dimensions. While the provision of electric power to non-electrified populations can be challenging, it is widely seen as a critical factor to advancing economic and human development. Despite significant investments by private and public organizations and widespread global progress, current efforts are moving too slowly to meet the United Nations' Sustainable Development Goal 7 of achieving universal access to electricity by 2030 (IEA, 2017). It is imperative to "think big" when considering solutions for this problem if we hope to make compelling progress towards achieving these international goals.

"Thinking big," is not always easy, however. Viewing the problem of universal electricity access from a systems-level reveals significant complexities related to humans, businesses, governments, and other institutions across a number of cultural, geographic, and legacy contexts. The implications of these considerations are compounded by significant technical and economic dimensions of complexity arising from the dynamic and networked nature of large-scale electricity infrastructure planning. Cost-optimal techno-economic plans can serve as the foundation for holistic planning approaches that further consider non-technical factors.

The technical complexity of electrification planning can be exemplified in part by the range of electrification modes available today. In addition to traditional electrification by grid-extension, off-grid mini-grids and stand-alone home systems have recently gained momentum as effective, alternative ways of providing access to energy. The IEA estimates that of the total investment that will be necessary to achieve universal electricity access by 2030, over 34% is estimated to be in mini-grids, with 29% in other off-grid products. Though numerous assumptions are required to make such estimations, the magnitude of the opportunity that off-grid solutions present cannot be overstated. Challengingly, institutions in developing regions today are generally ill-equipped to take full advantage of these opportunities, as grid-extension has represented the status-quo electrification mode across the world for well over a century. Rural electrification agencies, energy ministries, private investors, and entrepreneurs could benefit from knowledge of what the least cost electrification modes and system designs are over their territories of interest, to be used as a basis upon which to add further considerations.

The scale of the challenge associated with universal energy access, the amount of information involved, and the diversity of options for intervention compel the use of computer planning tools. As a result, research organizations have started to build and provide several of these automated tools, the number and quality of which has evolved rapidly in recent years. Utilities, governments, and development organizations have also responded to these opportunities by collecting information and improving the availability of digitized and georeferenced data for their jurisdictions.

This paper describes one of these computer models – the Reference Electrification Model (REM), developed by the MIT-Comillas Universal Energy Access Laboratory (UEA Lab) http://universalaccess.mit.edu – which we consider represents the state of the art in electrification planning. REM performs automated least-cost electrification design; it determines cost-optimal combinations of electrification modes for a given study region, including single building standalone systems (SA), isolated grids with local electricity generation or mini-grids (MG), and extensions of the existing distribution network (GE). REM performs this task with a very high level of spatial granularity, producing detailed designs down to the individual consumer-level. It prescribes network infrastructure layouts, local generation configurations, and storage options. These capabilities are intended to allow planners to make more informed decisions about electrification modes, budget allocations, and bills of materials; ministries and regulators can get quantitative support for policy design; and developers can gain detailed insights into the potential for off-grid systems in a region. REM can also facilitate participatory planning approaches by providing references for least-cost electrification designs that can be evaluated by different stakeholders. Technically objective model-driven prescriptions for range of scenarios and assumptions can help to elevate the content of collaborative discussions.

REM considers the specific demand profile of each customer (incorporating residential, commercial, and industrial loads) and determines the least-cost grid/off-grid electrification plan by comparing a large number of clustering alternatives through a combination of heuristic optimization, mathematical algorithmic optimization, and simulation algorithms. These algorithms account for estimated yearly weather conditions and demand profiles, targets of quality of electricity supply, the reliability performance of local distribution feeders, voltage and capacity constraints of lines and transformers, catalogs of power system components for grid extension and off-grid systems, any existing limits or targets in the use of fossil fuels or renewables or carbon emissions, and implications of the topology of the terrain: forbidden areas, use of prescribed paths such as roads or streets, and extra costs due to factors like altitude or the slope of terrain being considered.

REM has been applied to multiple real electrification planning problems, ranging from cases representing small areas with hundreds of customers to comprehensive analyses of entire countries with millions of them. A particular configuration of REM, named LREM (Local REM) has been applied to many cases representing villages or small regions to provide detailed electrification designs where all customers are connected to the same mini-grid.

Despite its capability to incorporate technical and economic features of electrification, REM is only a support tool in the electrification planning process. It should be acknowledged that political, administrative, regulatory, legal, social, and cultural factors, among others, also play critical roles.

This paper is structured as follows: Section 2 reviews existing computer-based electrification planning methods. The Reference Electrification Model (REM) is described in detail in Section 3, with special emphasis on the demanding input data and the technical procedures that the model requires. The description of the model is illustrated in Section 4 with a case example representative of the actual regional electrification planning studies performed with REM. The example includes descriptions of the input parameters, the look-up table of representative designs for mini-grid generation, the clustering results, and the final electrification plan. Examples of the utilization of LREM are presented in Section 5. Section 6 discusses the applications and limitations of the model, as well as enhancements that are still outstanding. The sections on conclusions (7), acknowledgments (8) and references (9) conclude the paper. An annex provides further details of the sensitivity analysis presented in Section 4.

2. Software support tools for electrification planning.

Models are used in various ways to support the complex sequence of decisions necessary to design or modify an electric grid, such as where and how to build the network, where to site generation, which technologies to use, etc. As off-grid electrification has increasingly entered the mainstream of electrification planning, there have been substantial developments addressing the unique challenges that both mini-grids and off-grid systems present.

The work reported in this paper contributes to two active areas of research: large-area electrification planning and single-system electrification planning. Large-area approaches de-emphasize local accuracy and instead prioritize the identification of trends over large regions, while single-system approaches lend themselves to more detailed data collection and scrutiny. The method we describe here contributes to both bodies of knowledge, since it is capable of producing very detailed cost-optimal solutions at all scales.

2.1 Large-area planning.

Large-area planning models evaluate various electrification options for a region and aim to identify the most suitable delivery modes for each considered consumer. Given their broad geographical scope, they frequently have to rely on highly aggregated or incomplete data about the layout and characteristics of the existing distribution network and targeted demand. Despite their usefulness in efficiently handling information pertaining to large areas, they are often limited in their capability to incorporate critical factors such as consumer preferences and other social, political, and administrative considerations.

A complete large-scale rural electrification plan consists of determining the “best” (in some prescribed sense) electrification solution. This solution is composed of the classification of different modes of electrification for a given set of customers (i.e., grid extension, mini-grid, or stand-alone system) and providing the technical and economic characteristics of that solution. This corpus of information is intended to assist in decision-making processes and facilitate the provision of electric power.

Several software tools have been developed to deal with this problem. Those based on Geographic Information Systems (GIS) typically group consumers into geometric cells that often represent villages, calculate the Levelized Cost of Electricity (LCOE) with grid extension and with off-grid alternatives, and suggest least-cost electrification modes. One of the most widely employed computer-based models that makes use of this general approach is the OpeN Source Spatial Electrification Toolkit (OnSSET), which was developed by the KTH Royal Institute of Technology and released as an open-source tool. This is a rather mature model and it is affiliated with several projects and studies (Mentis et al., 2017, 2016, 2015; Nerini et al., 2016). OnSSET makes use of geospatial information such as proximity to roads and the power grid, population density, and wind, solar and hydro potential to determine appropriate electrification solutions for each cell.

Another tool that relies on this approach is IntiGIS (Pinedo Pascua, 2012), which was developed at Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT, Spain) as an evolution of the SOLARGIS tool (Monteiro et al., 1998) and further efforts (Amador and Domínguez, 2005). IntiGIS also operates with cells and minimizes their

LCOE to obtain the electrification solution, emphasizing the relevance of GIS technology in rural electrification when gathering data such as wind speed and solar irradiation.

Similar procedures are followed by other methods described in the literature (Huld et al., 2017; Bertheau et al., 2016; Cader et al., 2016; Martinez-Cesena et al., 2015; Szabó et al., 2013, 2011; Kaijuka, 2007) as well as software tools (The World Bank Group, 2016; RE2nAF, 2016; ECOWREX , 2012).

Other large-scale approaches compare the cost effectiveness of village off-grid electricity supply to grid extension by estimating tradeoffs between the cost of local generation and grid extension layout (Deichmann et al., 2011; Banks et al., 2000). Logiciel d'Aide à la Planification d'Électrification Rurale (LAPER) determines the best electrification mode for a set of villages or settlements minimizing total investment and operation expenses (Rainer Fronius and Marc Gratton, 2001). Challengingly, LAPER requires its users to provide an initial network that connects all (or most) the settlements and then the model evaluates sequentially if they are worth disconnecting one line at a time. LAPER was used for rural electrification planning in Morocco (Soler et al., 2003).

Network Planner (Network Planner Website, 2017) is an open-source model developed at Columbia University that minimizes a cost function to determine the best electrification mode of a set of villages and the layout of the corresponding grid extension network. Network Planner has been used to provide assistance in electrification planning processes in Nigeria (Ohiare, 2015), Liberia (Modi et al., 2013) and Ghana (Kemausuor et al., 2014). (Parshall et al., 2009) describes the heuristic that Network Planner uses to calculate the grid extension layout. The researchers use Minimum Spanning Trees (MST) to evaluate the cost of extending the MV grid network to some area and to compare with that of electrifying that area with either diesel-powered mini-grids or solar home systems. While the model endeavors to make village-level decisions, the data in (Parshall et al., 2009) is aggregated at the sublocation level (within an average area of 15 km^2), differentiating sublocations only as high or low income. Furthermore, Network Planner does not account for grid reliability, a factor which can play an important role in grid extension decisions in rural areas.

Another tool that follows a similar approach is GEOSIM, which was developed by Innovation Energie Développement (IED). GEOSIM has been used in several countries in Africa and Asia ("GEOSIM clients," 2018) and the model has been applied to electrification projects for the World Bank and the European Commission ("GEOSIM projects," 2018). GEOSIM sorts villages according to their Indicator for Potential Development (IPD), selects a few of them to be "Development Poles" and clusters the villages around them using an algorithm based on the Huff model (Huff, 1963) before determining the electrification solution for each village.

There are also attempts to deal with this problem using classical optimization techniques. (Zeyringer et al., 2015) formulates a Mixed-Integer Linear Programming (MILP) problem and groups the consumers into square cells. However, these cells are very large and solar is the only off-grid technology considered. (Abdul-Salam and Phimister, 2016a) applies hierarchical lexicographic programming to the problem with three different objective functions, although the number of settlements that are electrified with grid extension designs is an input in this formulation. Finally, (Abdul-Salam and Phimister, 2016b) introduces a Mixed Integer Nonlinear Programming (MINLP) formulation and compares the results with (Parshall et al., 2009), although this approach assumes that the already-existing network consists of one single node to reduce the computational burden.

Although these tools provide useful insights, even if building-level information is available, they group the buildings into villages, settlements, or cells instead of operating at the individual consumer-level. Their network designs are based on geometric considerations involving distances and demand sizes, instead of applying power flows and electrical constraints. They do not optimize the generation designs of off-grid systems, and they do not account for non-served energy in their decision-making logic. In summary, electrification planning tools have traditionally made overly strong assumptions with unknown implications regarding the quality of their results and recommendations.

The most direct approach to overcome this limitation is to take the spatial granularity and the specification of the demand patterns to the individual consumer-level. In contrast with the abovementioned tools, this paper proposes a large-scale electrification planning model – the Reference Electrification Model (REM) – that (a) operates at the individual consumer-level instead of using aggregate villages or cell representations, (b) calculates network designs considering electrical constraints and specifications of real equipment, (c) incorporates topography in the optimization process, and (d) obtains generation designs using optimization techniques and simulation instead of rules based on a-priori-determined analytical expressions. Solving a large-scale problem with this level of detail is computationally expensive and it is necessary to balance accuracy in the electrification solution with computation time. An early version of REM is described in (Ellman, 2015) and further developments are presented in (Ciller Cutillas, 2016). This paper presents the current level of development of REM, which is presently still being enhanced in several aspects.

2.2 Local off-grid electrification planning.

Single system design models are particularly useful once a site has been identified for off-grid electrification, but they are also an integral part of large-area electrification planning processes. Local models have to solve two quasi-independent problems: the design of the local distribution network and that of local generation systems.

The general methodology for designing a local generation system consists of determining candidate designs and evaluating their performance. A variety of methods have been described in the literature for the optimal selection of local generation and storage. (Upadhyay and Sharma, 2014; Luna-Rubio et al., 2012) classify the main methods of solving this problem. Some of them apply classical optimization techniques such as linear programming (Huneke et al., 2012; Erol-Kantarci et al., 2011) or metaheuristic algorithms (Katsigiannis et al., 2012, 2010; Nasiraghdam and Jadid, 2012; Li and Zhou, 2012; Moghaddas-Tafreshi et al., 2011; Bala and Siddique, 2009). The moderate size of the local off-grid electrification problem allows employing multicriteria approaches, involving other objective functions that go beyond costs, such as emissions minimization (Wang and C. Singh, 2009).

There are a few quite mature models that have focused on just the local supply generation problem. The best-known is HOMER (Lambert et al., 2006), which was developed by the National Renewable Energy Laboratory (NREL). This tool has been downloaded over 150,000 times from users of more than 190 different countries ("HOMER energy," 2018). Other tools that are worth mentioning are DER-CAM (Bailey et al., 2003), created by Lawrence Berkeley National Laboratory (LBNL), which uses a MILP formulation, and iHOGA (Dufo López, 2018), developed by the University of Zaragoza in Spain and that applies genetic algorithms.

Other tools are also relevant in the context of local off-grid generation. RETScreen makes use of feasibility-analysis (Adam et al., 2015; Thevenard et al., 2000) and Hybrid2 uses simulation (Manwell et al., 1998; Baring-Gould et al., 1996; Green and Manwell, 1995). Hybrid2 is now no longer supported. A comprehensive review of these software tools is provided in (Sinha and Chandel, 2014).

The network component of the mini-grid design problem obtains the network layout, given the location and demand of the consumers and oftentimes the location of the generation site in addition. There is plenty of literature about network distribution planning (Georgilakis and Hatziargyriou, 2015), where both classical optimization techniques (Paiva et al., 2005) and metaheuristic methods (Koutsoukis et al., 2014; Mendoza et al., 2013) have been applied. However, this problem has not been thoroughly studied from the rural electrification perspective.

Village Power Optimization model for Renewables (ViPOR) (Rout and Parida, 2013) designs distribution networks for off-grid systems with a simulated annealing algorithm (Lambert and Hittle, 2000), although this software is currently unsupported. There are other methods for rural electrification network design (Kocaman et al., 2012) but they do not guarantee feasibility with regards to technical electric power systems-related constraints.

(Mateo Domingo et al., 2011) describes the Reference Network Model (RNM), which is a large-scale network design tool developed at IIT-Comillas in Madrid, Spain, which can also be used in the design of the network component of mini-grids. The model designs the minimum-cost network that meets quality-of-service specifications, using a user-provided catalog of equipment to specify distribution infrastructure down to the individual consumer-level. A key feature in the development of RNM pertains to the high levels of scrutiny it received: its results were validated by the Spanish distribution utilities; RNM was then accepted by Spanish regulators as a decision-support tool to determine appropriate remuneration figures for electric power distribution. RNM has been used for this same purpose in several other countries and in many technical studies.

REM uses RNM as a submodule to calculate network designs for mini-grids and grid extensions, as we describe in this paper. When applied to large-scale electrification planning, REM has to evaluate mini-grid configurations numerous times, each of which requires the design of generation assets and network layouts using RNM. REM can also be used for smaller-scale mini-grid design as LREM (its “local” mode). This configuration optimizes the generation design of a given mini-grid, its associated hourly dispatch, and the network layout. While doing this, LREM considers investment and operation costs plus penalties for non-served energy. (Li, 2016) describes the LREM functionality and applies it to the village of Karambi in Rwanda. (Brusnahan, 2018; Cotterman, 2017) also perform mini-grid analyses using LREM in villages located in India, Nigeria, and Rwanda.

It can be concluded from this review of large-area and local off-grid electrification planning models that REM stands out from previously existing approaches by providing system designs at any geographical scale, working at the individual customer-level, employing full representations of each customer’s hourly demand patterns, respecting the physical laws and constraints of power systems, explicitly modeling reliability targets and costs of unserved energy, accounting for the consideration of topographical characteristics, and employing optimization methods to find least-cost combinations of electrification delivery modes.

3. The Reference Electrification Model (REM).

In this section, the model is explained in detail. After a general overview of REM, the complete set of input data required to run the model is described, reflecting all the different aspects that must be considered when using the model to support electrification planning. Collecting data to run REM is typically the most time-consuming activity in actual applications of the model. Practical guidelines to gather data are subsequently presented, followed by a description of the most relevant subproblems and technical procedures embedded in REM. Finally, the outputs that REM generates are presented.

3.1. REM overview.

REM finds the electrification plan that meets a given estimated demand for individual customers in a territory at minimum total cost, while satisfying the power system technical constraints as well as other user-defined constraints regarding the reliability of supply, generation mix, administrative requirements, and priorities or limits regarding modes of electrification (e.g. a pre-established target for grid extension, or a limit to the number of households to be supplied with mini-grids). The demand is defined at very high levels of spatial and temporal granularity: hourly demand patterns for each individual customer (building). In general, the electrification plan consists of a combination of electrification modes: extension of the existing grid, off-grid mini-grids, and stand-alone systems. Systems prescribed may range in size from small home solar kits to large and sophisticated mini-grid and grid-connected systems for schools, clinics, mines, and other commercial, industrial, or institutional facilities.

When deciding among the alternative electrification modes REM may consider the following factors:

- For grid connection:
    - Layout and technical characteristics of the existing grid, and cost of extending the MV and LV networks.
    - Required upstream supply costs of generation and networks.
    - Reliability of the existing grid.
    - Catalog of available equipment with technical and economic characteristics and applicable grid codes.
- For off-grid supply systems:
    - Costs of local generation, with costs and availabilities of local resources including solar and diesel (wind, mini-hydro and biomass models are currently under study)
    - Costs of extending the local network to every customer with either DC or AC components.
    - Customer preferences between standalone systems and mini-grids.

- Extra costs for making mini-grids "grid-compatible", so they have the flexibility to connect to the main grid at a future date.
- Dispatch strategies of local generation and storage, as well as for any applicable demand management schemes.
- Desired reliability of supply.

When evaluating the cost of the internal network of a mini-grid or of a grid extension, REM has to design the minimum cost network that meets all prescribed technical requirements. This network-design process has to be done numerous times (many alternative subsystems or clusters), even for problems of moderate size. For this task, REM employs the greenfield network-design software called the Reference Network Model (RNM), which was already mentioned. RNM employs equipment from a prescribed catalog, designs networks that meet electrical constraints, and accounts for topological features in the considered region: slope and altitudes of the terrain, forbidden and penalized zones, and administrative data such as village boundaries (different technical requirements may apply in rural, semi-urban and rural areas, for instance).

When addressing the different procedures embedded in the determination of an electrification plan, REM uses a mix of established mathematical optimization algorithms and heuristic methods. REM seeks the minimization of a combination of actual costs and social costs. Actually incurred costs are related to investment, operation, maintenance, and management activities, which can be directly quantified. Social costs measure the loss of utility or welfare to the end consumers resulting from poor service quality and potential limitations in electricity utilization associated with their mode of connection.

The following outputs are typically obtained when REM is applied to some specific territory:

- The optimal groupings of individual consumers into electrification clusters so that total system costs are minimized. These clusters may denote groups of customers to be connected to separate mini-grid systems, groups to be connected to the existing grid, or clusters of single customers to be supplied with stand-alone systems.
- The optimal generation mix and network layout for each of the off-grid mini-grids.
- The optimal network layout for each cluster that will be connected to the grid.
- A detailed description of the optimal plan with information pertinent to decision-making including total cost breakdowns, expected reliability data, GIS files specifying network layouts, generation and storage specifications, bills of materials, summary charts, geo-referenced maps of system designs, and reports in text and spreadsheet formats.

3.1.1. Stages in the utilization of REM.

The standard REM process is structured into five sequential stages:

I. Data preparation. This stage includes partially automated tools used to generate required inputs. For example, a computer vision system that extracts building footprints from satellite images is used to identify customers when such information is not readily available and doing so manually is too expensive or time-consuming. Other tools employing machine learning concepts classify customers as either electrified or non-electrified given correlated geospatial features. Subsequently, customers may be characterized as belonging to one of several customer types and to be of a certain size. Each customer can then be assigned a characteristic demand profile derived from empirical data; demand profiles may also be estimated by aggregating typical consumption patterns from constituent electrical appliances.

II. Mini-grid generation design. Optimal generation and storage have to be determined for each potential grouping of customers that is evaluated, considering its aggregated load profile, the available catalog of system components and some pre-selected dispatch strategy. In order to save computation time, the designs for some number of representative combinations of consumers are solved in advance and stored in a look-up table, so that future designs for other combinations of customers can be quickly obtained by interpolation. Though the look-up table represents only approximate designs, it is used in the clustering process to speed up the estimation of local generation cost for each candidate mini-grid.

III. Clustering. The customers are grouped into a hierarchical structure of off-grid and grid-extension clusters. Both clustering processes consist of bottom-up greedy algorithms that join customers into groups if the expected cost of being connected is lower than the expected cost of being electrified separately. Here, robust cost estimations (using partial and uncertain information) are critical to make sound decisions.

IV. Final designs. REM explores the structure of clusters obtained in the previous stage and calls RNM to evaluate precise network designs and costs. It then determines the optimal combination of stand-alone systems, mini-grids, and grid extensions. During this process, proposals for mergers of clusters and proposals for grid connections of clusters are accepted or rejected on the basis of design cost.

V. Post-processing and reports. REM generates several reports containing plots, tables, geospatial data files, and other items, providing all information of interest on the cost-optimal designs that REM has found.

The modular structure of REM allows alternative strategies for steps (I), (III) and (IV). For instance, instead of the bottom-up clustering approach used originally in REM pertaining to (III), a full grid-extension solution can be generated initially, with subsequent and systematic disconnection algorithms to identify off-grid solutions (a “top-down” clustering approach) as described in (Oladeji, 2018).

3.2. REM input data.

A REM study case is characterized by a set of files describing the existing and potential electrical demand in a region, physical characteristics of the region, existing infrastructure, available electricity supply technologies, and information regarding design preferences.

The different types of files are classified into the following categories:

- Local information: Information particular to a given analysis region:
    - Demand (buildings, types of customers, demand patterns).
    - Existing network (line segments and their types, transformers).

- Topography and geography (local solar input characterization, elevation, slope of the terrain, forbidden areas).

- Equipment catalog: Technical and economic parameters of available electrification components for both distribution network extension and off-grid electricity supply:
    - Networks (types of lines and transformers that can be used, at the different voltage levels).
    - Off-grid generation (solar panels, diesel generators, batteries, power electronic equipment).
- User options: User options are specific to the particular case study and are structured into eight blocks of related configurations:
    - Workspace definition.
    - Electrification problem.
    - Case-study specification.
    - Electrification criteria.
    - Financial, business, and general cost parameters.
    - Topography/geography.
    - Network design.
    - Mini-grid generation.

Figure 1 shows how the parameters of the "User Options" file are organized in blocks, and also how the different blocks contain references to the rest of input data files used by REM.

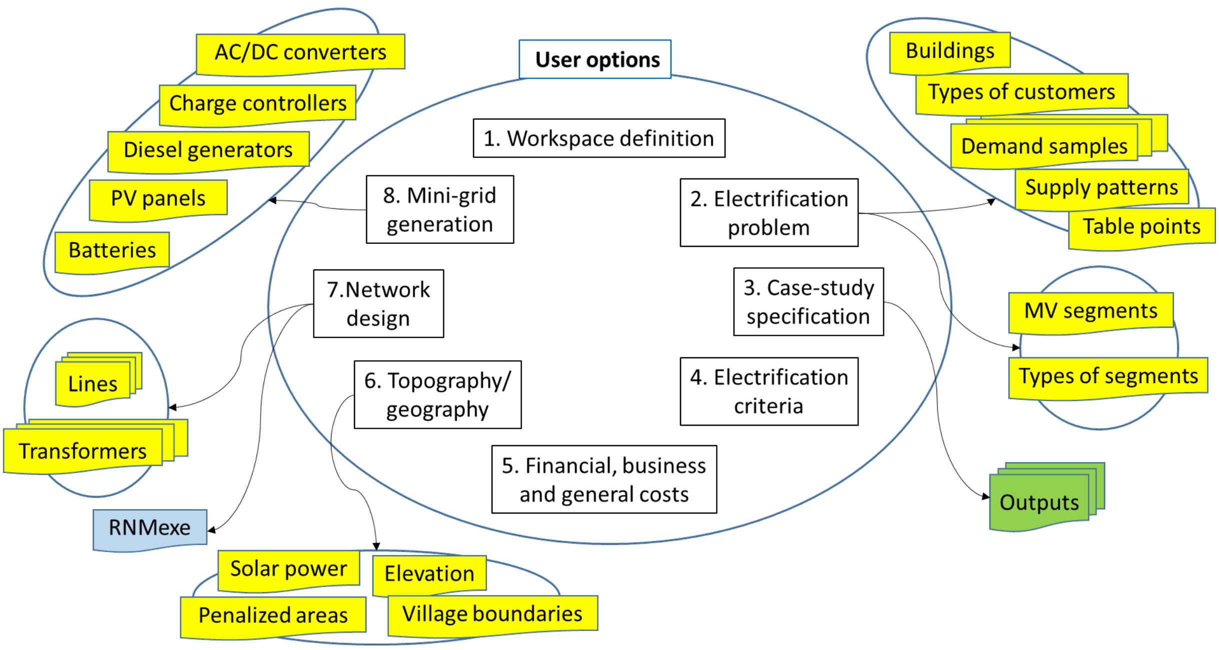

Figure 1: Organization of REM inputs.

The contents of the different blocks of parameters and the types of data files they refer to are briefly described below.

3.2.1. *Workspace definition.*

This block defines the study case in the context of a multi-project and multi-user tool, by means of parameters such as the identifiers of the project, the user, and the study case.

The coordinate systems and the transformations used for the geo-referenced data are also defined. REM works internally with a user-defined (X, Y) planar system, but the original inputs and the final outputs may be handled in absolute latitude and longitude coordinates for consistency and GIS-compatibility reasons.

3.2.2. *Electrification problem.*

This block comprises the main input data of the electrification problem statement: the demand to be satisfied and the characteristics of the existing electric system. Figure 2 illustrates how this information is organized. The parameters included in this part of the configuration file describe the region under study and the option to apply time and power limitations of supply to the demand patterns.

					Type of file	Comments
Local information						
	Demand					
		Buildings			Buildings	
		Types of customers			Types of customers	
		Demand patterns				
			Demand samples		Samples	One file for each demand pattern
			Supply patterns		Supply	Optional
			Look-up table points		Table	Optional (save time in REM clustering)
	Existing network					
		HV network				Not used yet
		LV network				Not used yet
		MV network				
			Feeders segments		Segments	
			Types of MV segments		Segment types	Optional, default type may be used

Figure 2: REM input files related to the electrification problem.

The "Buildings" file comprises the list of customers, each one with its coordinates, electrification status (binary), and type of customer. The demand assigned to each type of customer is defined separately, as described below.

The "Customer types" file relates each customer type to a demand pattern. It also allows the pattern of demand of a type of customer to be approximated as a linear combination of "basic" demand patterns (see sections 3.3.2, 3.4.1.3). This feature is used to save time in further phases of REM by dimension-reduction and a look-up table of pre-calculated designs for the interpolation of off-grid generation costs. This look-up table is contained in the "Look-up table points" file. For further details on the treatment of consumer types, see sections 3.3.2 and 3.4.1.3.

The demand patterns are defined by full-year timelines of hourly power consumption for both critical and non-critical demand. The "Demand Samples" file, which specifies one timeline for each demand pattern, includes several storylines accounting for randomness in demand. Finally, the "Supply Patterns" file allows the definition of supply limits for demand patterns in terms of maximum power and time intervals.

In the current version of REM, only the existing MV network is used to derive grid extensions. Two files describe the existing network: the "Feeders segments" file and the "Types of MV segments" file. The "Feeders segments" file comprises a set of segments, with their locations and types. The "Types of MV segments" file defines the energy costs and reliability profiles of each type of segment). This file is optional because uniform default values can be used for the cost and reliability of the entire network.

3.2.3. General execution options for the case study.

This block of the configuration file controls the general execution details of a particular case study. Users can define whether they want to run the model as REM or LREM, defining whether customers should be grouped into clusters or all connected to the same mini-grid network. Users can also choose mini-grid dispatch strategies, the type of clustering algorithm used, and desired output files.

3.2.4. Electrification criteria.

This block of the configuration file defines overall targets for the electrification plan. The most important ones refer to required levels of quality of service and the mix of delivery modes (i.e., grid extension, mini-grids, and standalone systems) used to meet the targets.

- Quality of Service. Minimum acceptable levels of quality of supply in grid-extension and off-grid systems, as well as the social cost of non-served energy are included. Non-served energy costs are further differentiated for critical and non-critical demand, as well as the social cost of low-quality (and low-cost) electrification solutions such as solar kits.
- Policies. By default, REM will search for the least-cost electrification plan. Ad hoc input "policy penalties" or "customer preferences" to some features of the plans allow the user to bias the final solution towards fewer or more customers served by grid extensions, mini-grids, or standalone systems. Other parameters can define relative or absolute cost thresholds for the entire plan, establish a minimum size for the mini-grids, force connectivity within the boundary of a village, and force grid-connections for buildings situated within a short distance to the existing grid.

3.2.5. Financial, business, and general cost parameters.

An electrification plan extends over many years. Since a plan includes a variety of technologies and delivery modes, it is not trivial to compare different plans in terms of total cost over a long period. REM addresses this difficulty by minimizing the cost of supply for just some chosen future year, by comparing the equivalent annuity (i.e. assuming some evolution of costs in time and the different economic lives of the physical assets employed in the plan) for each plan for that future year, and choosing the plan with the minimum value. The annuity includes CAPEX, OPEX, social costs, and policy penalties. Though they are considered together in the cost function, these different costs are carefully separated in the final solution reports.

The catalogs of components contain the corresponding investment and operation costs. Social and policy cost factors are described in Section 3.2.4, the “electrification criteria” block. Other parameters that are needed to compute the equivalent annuity include:

- The design horizon (i.e., the future year for which REM obtains the optimal plan), demand growth rate, system lifetimes, and discount rates that are appropriate for the considered planning situation: government or rural electrification agency, electric utility, private investor, development agency or other.
- Per-customer connection costs for each delivery mode, functions for mini-grid management costs that account for economies of scale, and labor cost/hour to compute maintenance costs.
- Default cost of the energy delivered to the distribution network and reliability characteristics of the upstream wholesale supply.

3.2.6. Topography/geography.

This block contains the input data related to geographic characteristics of the region under study including its solar resource history, altitude maps, penalized or forbidden areas for power lines, and administrative geographic boundaries that may add constraints to the clustering process (see Figure 3). Depending on the geographic information available, the relevance of the topographic features, and the desired level of detail, users can choose to neglect some of these features and reduce computation times.

					Type of file	Comments
Local information						
	Geography and Topography					
		Solar power			Solar	
		Terrain elevation			Elevation	Optional (if required and available)
		Penalized areas			Areas	Optional (if required and available)
		Village boundaries			Boundaries	Optional (if required and available)

Figure 3: REM input files related to geography and topography.

The “Solar power” file corresponds to the hourly history of the local solar resource for a representative year. Historical solar irradiance data is assumed to well-approximate future patterns for a given area; however, different and more sophisticated forecasting methods may also be applied.

The “Terrain elevation” file is a raster map with altitude values that allows the use of three types of local penalty factors pertaining to the cost of line deployment: (1) altitude, (2) slope, and (3) 3-D length adjustments. The “Penalized areas” file is a list of polygons encircling areas with associated penalty factors, where building and maintaining network infrastructures is costlier or simply forbidden.

Finally, “Village boundaries” is a file with polygons describing the administrative boundaries of villages. For instance, the user may optionally require all the buildings within the village boundary to be supplied with the same delivery mode.

3.2.7. Network design.

This block contains parameters that are needed for grid-extension and mini-grid network design. They are needed for both the utilization of the RNM model and in specific REM algorithms. RNM designs grid extensions as well as the internal networks of mini-grid clusters and REM estimates the incremental network costs of connecting clusters to other clusters and to the main grid.

					Type of file	Comments
Equipment catalogs						
	Network design					
		Grid extensions				
			Lines			
				HV	Nd1	
				MV	Nd1	
				LV	Nd1	
			Transformers			
				HV/MV	Nd2	
				MV/LV	Nd2	
		Microgrids				
			Lines			
				MV	Nd1	Optional, if different technology
				LV	Nd1	Optional, if different technology
			Transformers			
				MV/LV	Nd2	Optional, if different technology

Figure 4: REM input files related to networks design.

This block also contains references to external files. The files related to network design in the current version are shown in Figure 4 and described below:

- Catalogs of HV, MV, and LV lines, and HV/MV and MV/LV transformers. Lines and transformers are described in terms of power transfer capacities, impedance, and cost parameters (investment and maintenance).
- With this information, an RNM executable file is obtained, which can be run as an external executable file. As such, it is represented as an input file in Figure 1.

REM assumes standard 3-phase networks with only three voltage levels (HV, MV, LV). The use of other voltages or single-phase circuits must be emulated using equivalent components in the catalog, in which the main defining parameters are kept (i.e.., costs, power capacity, voltage drops, and losses) while impedances are conveniently modified.

3.2.8. Mini-grid generation.

This configuration block defines how off-grid generation systems are designed. Currently, only AC systems with diesel, PV panels, and batteries are considered, along with requisite charge controller and inverter hardware. Figure 5 depicts the most comprehensive design that is currently modeled in REM. It includes components that may not appear in some designs because of economic or environmental reasons. Such environmental reasons are further described in Section 3.3.5.2.

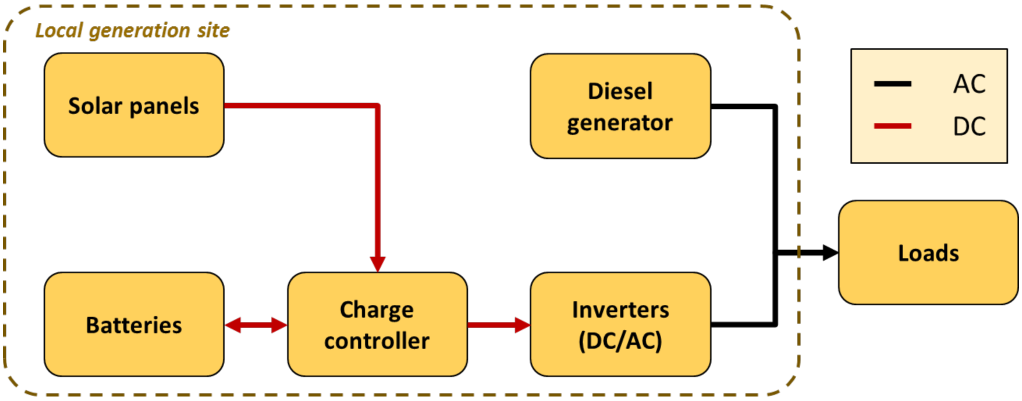

Figure 5: General structure of a generation site in REM.

The parameters included in this block are related to costs, to the optimization process, and the simulation of the mini-grid dispatch and operation processes:

- Parameters related to costs. Parameters include the diesel fuel cost, functions defining economies of scale, overall loss estimation, and operation and maintenance cost-factors for different sites and configuration sizes. This block also includes a parameter that decides whether the generation costs should be calculated by a computationally costly optimization process or by a simple interpolation in a precomputed look-up table.
- Parameters related to the optimization process, such as the algorithm selection or the constraints to be applied to the use of some technologies – as it is the case with diesel.
- Selection of the generation dispatch strategy. Several alternative approaches for generation dispatch can be chosen, including "load following" (see Section 3.4.1.1) and "cycle charging." These strategies have different operating characteristics and properties, mainly related to how they solve the conflict between saving diesel and keeping the battery charged.

The block also includes references to input files related to mini-grid generation designs, as shown in Figure 6.

			Type of file	Comments
Equipment catalogs				
	Microgrid generation design			
		AC/DC converters	Coverters	
		Charge controllers	Controllers	
		Diesel generators	Generators	Optional, if diesel is forbidden
		PV Panels	Panels	Two technologies (in current version)
		Batteries	Batteries	Two technologies (in current version)

Figure 6: REM input files related to mini-grid generation design.

There are five different files that contain technical (static and dynamic) and economic (overnight, and operation and maintenance cost) information for the different types of generation-related components: converters, controllers, diesel generators, PV panels and batteries. The REM user may remove or limit the diesel option, which in some regions may be forbidden. Regarding the utilization of PV solar panels and batteries, only two module sizes are allowed in the current version of REM, one for small standalone systems and the other for large generation sites.

The current version of REM uses the same catalog of components in the design of mini-grids as it does for stand-alone systems. The use of solar kits as an alternative for households is not automatically incorporated in the optimization process, since this would produce discontinuities in the standard optimization logic. Solar kits are only considered in a post-optimization phase, as an alternative for stand-alone systems with conventional technologies.

3.3. Getting REM input data in practice

Recent experience in the utilization of REM for diverse situations has shown that at least 80% of the time and effort required to produce an electrification plan is spent in data gathering and preparation. This process includes (a) identifying the existence of data, (b) identifying and contacting its sources, (c) defining what is needed, (d) obtaining permission to use some proprietary data or eliminating confidential information, (e) collecting the data, (f) verifying and cleaning it, and (g) making the data ready to be used in REM.

This section explains procedures used in different situations to obtain the various types of data that REM uses as input. In some cases, the data are available from some institution and they only have to be transferred to REM users and adapted to the required format. In other cases, specialized algorithms have been developed to obtain the data.

3.3.1. Determining Building Locations and Building Electrification Status

Planners need to know where buildings are located in order to plan on how to provide them with electricity. They also need to make determinations on whether these buildings are already serviced with electric power. In this section, we discuss three steps along our automatic data procurement pipeline for Regional REM: (1) building footprint extraction from satellite imagery, (2) load localization, and (3) electrification status estimation.

First, building footprint extraction involves the pixel-wise classification of satellite and aerial imagery. Building pixels of high-resolution imagery are classified as either belonging to buildings or to background. Secondly, load localization refers to the delineation of discrete customer units. In our treatment, we perform load localization as a step subsequent to building extraction. Finally, electrification status estimation corresponds to the classification of these buildings as currently electrified or non-electrified. The pipeline presented describes a procedure for producing approximate inputs for REM quickly and with sufficient quality for many large-scale plans. Ongoing efforts are aimed at improving each of these steps along the pipeline.

Choices on whether to pursue such automatic methods as opposed to manual ones depend on resource constraints and study requirements. Automatic methods afford the ability to scale techno-economic analyses to large regions at low cost; however, they are generally less accurate than manual methods (e.g., human annotations, ground surveys, etc.). In many cases, it is appropriate to pursue hybrid automatic-manual approaches and iterative methodologies.

3.3.1.1 Building Footprint Extraction

Building footprint extraction is commonly done using both manual and automatic methods. The largest and most notable manual building labeling endeavor is the OpenStreetMap (OSM) project. OSM provides free and open detailed building and street annotations using a crowdsourcing-based approach: millions of participants conduct ground-based surveys and perform manual labeling on top of aerial imagery (OpenStreetMap, 2017). While OSM rivals proprietary sources in terms of size and granularity of its map data, the quality of its data is inconsistent (Yuan, 2016). The availability of OSM's data is limited in developing countries and this is especially true in rural areas. Automatic methods are required to procure complete building data sets in these regions for large areas, without performing resource-intensive surveys and manual labeling. Convolutional neural networks (ConvNets) are the most accurate and effective automatic methods to date for building footprint extraction from satellite and aerial imagery as evidenced by the recent SpaceNet Competitions for building footprint extraction hosted by DigitalGlobe (Lindenbaum, 2017).

Ever since the convolutional neural network AlexNet won the ImageNet competition in 2012 with a 10.8 percentage point margin, ConvNets have exploded in popularity for computer vision tasks. They have often proven more effective than other contemporary methods for computer vision problems (MIT Technology Review, 2014). Building extraction from satellite and aerial imagery is no exception. Mnih et al. apply ConvNet architectures in 2010 to perform post-classification on neural network outputs for road detection (Mnih and Hinton, 2010). They also use ConvNets with untied weights and robust loss functions for high performance extraction (Mnih, 2013; Mnih and Hinton, 2012). Among subsequent academic studies, Yuan uses a signed distance function from building boundaries for the representation of ConvNets outputs and shows how this can benefit classification performance and enable the interpretation of fine-grained labels for border boundaries (Yuan, 2016). Chartock et al. explore the use of fully convolutional neural networks for bounding polygon extraction on building footprints (Chartock et al, 2017). Finally, Zhang et al. discuss Facebook's efforts to generalize these methods to perform building detection on a global scale with 500TB of imagery (Zhang et al., 2017).

Facebook's efforts are indicative of greater industry interest in object extraction from satellite imagery. Facebook is working on extracting building footprints from satellite imagery to help inform its Internet access efforts. In 2016, the company announced that it will release a 5 meter resolution data set for numerous countries around the world in partnership with the World Bank and Columbia University's Center for International Earth Science Information Network using DigitalGlobe's high-resolution satellite imagery (Gros and Tiecke, 2016; Tiecke, 2016). At the time of writing, population estimates for 24 countries have been released on the Center for International Earth Science Information Network's High-Resolution Settlement Layer website; however, they are only available at ∼30 meter resolutions (Columbia University Center for International Earth Science Information Network, 2018). In addition, though Facebook's access to high resolution DigitalGlobe imagery affords the possibility to release building-level GIS data, the population estimates publicly released in the High-Resolution Settlement Layer data sets are derived from aggregate census metrics and may lack levels of precision desired for many infrastructure planning endeavors. In essence, the 30-meter resolution pixels provided can be interpreted as binary classifications for whether buildings exist in the corresponding areas. Population estimates for these pixels are derived from region-level aggregate data, not corresponding satellite imagery at full resolution.

In the following sections, we describe a basic system for georeferenced building footprint extraction based on Long and Shelhamer et al.'s approach of Fully Convolutional Networks (FCN) for semantic segmentation (Long et al., 2015). Though FCNs are no longer state-of-the-art for semantic segmentation tasks in computer vision, they are well documented, easy to use, proved to be effective for building-footprint extraction, and serve as a benchmark for further research. In this section, we describe general considerations around the procurement of training data for this task, data sets used in an illustrative case study showing the importance of data quality, and results for this case study. Extended descriptions of each of these topics are given in (Lee, 2018).

Training data

The procurement of training data for supervised machine learning is often a time and resource-intensive endeavor. The compilation of training data for building extraction is no different. The models described for semantic segmentation require training data where annotations are captured at the pixel-level. While the OSM data set provides manual labels that may seem promising for model training, its sparsity and inconsistency in developing countries and its potential misalignment with satellite imagery decrease its usefulness for our application. Due to these considerations and the fact that our building extraction models may not be highly generalizable across regions, we find it is often beneficial to procure training data for regions of interest using annotation tools for binary image classification and for drawing polygons, as described in (Lee, 2018).

Data

The studies presented use geospatial vector data from Varshney et al. corresponding to 596 buildings from 10 rural villages in Odisha, India. Color balanced and orthorectified images of the area from Varshney et al. are also used, which were originally taken by DigitalGlobe's WorldView-2 Satellite at 50 cm resolution. The image has dimensions of 13,488 x 10,925 pixels, spanning just less than 37 km^2 (Varshney et al., 2015). Models trained and tested using these images are compared to those using lower-quality imagery obtained with Google Maps API at zoom level 18, which corresponds to ~60 cm resolution imagery. Additional preprocessing and train/test set details for the case study presented are described in (Lee, 2018).

Image tiles from the WorldView-2 and Google Maps data sets and their corresponding ground truth annotation are shown in Figure 7. In the ground truth mask, black pixels denote background area, red pixels denote area covered by buildings, and tan pixels show areas that are either missing labels or correspond to ambiguous regions – so they are ignored during training.

FCNs for Building Footprint Extraction

We fine-tune FCN models for semantic segmentation based on an ImageNet VGG Very Deep 16 model, incorporating Long and Shelhamer et al.'s skip architecture with lowest stride size of 8 pixels. We present qualitative results in Figure 7. This figure shows sample building segmentations after fine-tuning and testing on WorldView-2 and Google Maps imagery after 35 and 100 epochs. Table 1 provides common metrics for these models with regards to the assessment of semantic segmentation performance including pixel accuracy, mean accuracy, background intersection over union (IU), building IU, and mean IU. Please refer to (Lee, 2018) for metric definitions.

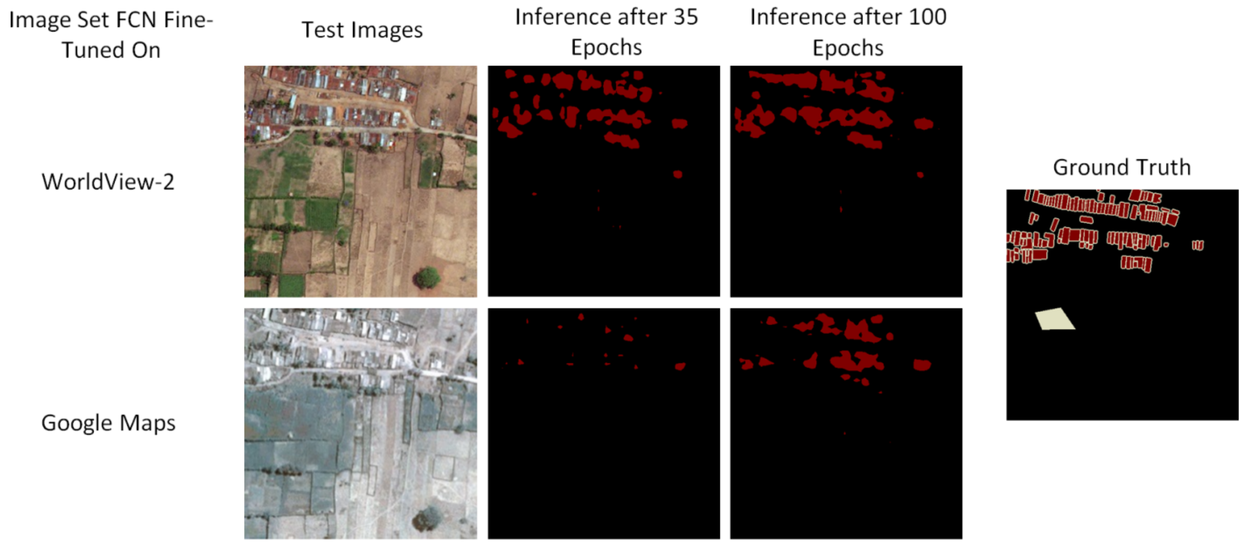

Figure 7. Inferences from ImageNet VGG Very Deep 16 models of the fcn8 type that were fine-tuned and tested on WorldView-2 images (top) and Google Maps (bottom) for 35 (second column) and 100 epochs (third column) (Lee, 2018).

Test Set	Epochs	Pixel Acc.	Mean Acc.	Backgroun d IU	Building IU	Mean IU
WorldView-2	100	99.96%	79.14%	99.96%	47.19%	73.58%
Google Maps	100	99.95%	65.40%	99.95%	26.67%	63.31%

Table 1. Building footprint extraction metrics comparing FCN networks trained and tested on both WorldView-2 and Google Maps imagery.

FCN models fine-tuned with WorldView-2 data showed more desirable error metrics than those fine-tuned with WorldView-2 imagery. After 100 cycles, the WorldView-2 fine-tuned models achieved 47.19% building IU and 73.58% mean IU, while the Google Maps fine-tuned models only achieved 26.67% and 63.31%, respectively. The differing qualities of detection can be seen when comparing inferences in the first and second rows of Figure 7. The superior results obtained from fine-tuning with the WorldView-2 dataset owe credit to the higher resolution, improved color balance, and higher contrast of these images. The Google Maps images, in contrast, had faint ``Google" watermarks, artifacts from image strip stitching process, and poorer overall image qualities.

These results demonstrate that contemporary ConvNet models for semantic segmentation are capable of automatic building footprint extraction from satellite imagery and that image quality is highly important. The ultimate benefit of using these tools is that they can scale massively in the presence of satellite imagery of adequate quality and with enough training data. Investments in improved image quality and training data should be made with consideration of alternatives and available resources.

3.3.1.2 Load Localization

Load localization refers to the process of identifying connection points for individual buildings and characterizing the potentially latent load profile associated with each of them. This is challenging because the process of converting building footprint extractions (which may reflect multiple buildings within a single contiguous group of pixels as shown in Figure 7) to individual customer points is non-obvious, and because information for determining load profiles is likely not present in satellite imagery alone. While the problem of load profile assignment has been largely unstudied and currently requires a number of assumptions, a few potential solutions exist for identifying individual buildings.

Connection points for individual buildings may be obtained by defining polygons that characterize building shapes, producing rasters for building boundaries, or by sampling points from contiguous groups of pixels denoting building footprints. Varshney et al. describe a polygonization method aimed at fitting polygons onto individual buildings given a set of pixel-based inferences. This provides approximations on where distinct buildings exist and provides a measure of their footprint sizes. Nevertheless, the authors note that the polygonization method is limited in its ability to distinguish between adjacent buildings (Varshney et al., 2015). Yuan's approach for describing buildings using a signed distance function from their boundaries in convolutional neural networks may be useful for this application. As mentioned previously, the signed distance function enables the definition of fine-grained labels for building boundaries (Yuan, 2016). It remains to be seen whether this approach is efficacious for identifying individual buildings in rural areas of developing countries. The data set used by Yuan is comprised of 0.3 m resolution imagery for Washington D.C.; building rooftops in these images are much more clearly defined and easily distinguishable than they are for the 0.5-1.0 m resolution imagery that is more commonly available for the developing areas. Chartock et al. also use convolutional neural networks and signed distance representations of buildings but have the explicit goal of producing bounding polygons. The do this using a post-processing step based on the Marching Squares algorithm for contour-finding (Chartock, 2017). Finally, Lee presents simple algorithms for distinguishing buildings from one another in satellite imagery based on sequential sampling and the delineation of exclusion zones. The approach relies on census or other information that can inform the definition of an average number of pixels per building (Lee, 2018).

The efficacy of the different approaches defined above for identifying connection points on individual buildings have not yet been compared for master planning and is the subject of future work. The choice of approach is likely also dependent on the method used for characterization of load profile, which itself may be dependent on data availability, generalizability, and other factors. Approaches for estimating load using building polygon or boundary information may rely on characterizing relationships between electricity consumption and building footprint area, location, and neighborhood building density. If a linear relationship is assumed between electricity consumption and building footprint area, the connection point sampling approach proposed by Lee may be appropriate. This assumption would imply that buildings with twice the footprint area would have twice the load and can effectively be modeled as two separate neighboring buildings. Load localization and characterization is an important area for continued research.

3.3.1.3 Electrification Status Estimation

Information regarding the current electrification status of buildings is imperative for planning activities. This information allows planners to avoid planning for duplicative infrastructure and ensure their plans meet the public's needs. Electrification status information also enables the assessment of technology choices; it can inform the use of techno-economic models such as REM that determine the attractiveness of off-grid technologies relative to modes of grid extension. Although distribution companies in developed parts of the world generally have a wealth of digitized infrastructure data, their counterparts in developing regions are consistently less informed. Numerous distribution companies in regions with low rates of electricity access lack adequate structured information regarding their low-voltage distribution lines (Lee, 2018). Although data collection and digitization efforts have commenced in some of these regions since then, requisite data on electrification status is still largely missing.

Only a few approaches for electrification status estimation have previously been reported on in the literature. Doll and Pachauri estimate electrification status by assuming that zero light intensity in DMSP-OLS annual composite nighttime light images confers lack of electrification (Doll and Pachauri, 2010). While Doll and Pachauri are able to expand their analyses to very large regions with ease, their assumption is questionable. Buildings that are located in areas that have non-zero nighttime lights signal may be non-electrified and conversely, buildings that are located in areas with zero-valued nighttime light signal may be electrified. Min et al. elucidate the inadequacy of Doll and Pachauri's assumption, finding that nighttime lights imagery most strongly reflects the presence of streetlights and is not on its own a strong indicator for household electricity use (Min et al., 2013). As such, this methodology is unsuitable for the infrastructure planning activities we propose.

Min et al. consider energy access in Senegal and Mali at the village-level for the year 2011. They compare night-time light output from the DMSP-OLS sensor against survey data representing 232 electrified and 899 unelectrified villages. The authors present a logistic regression model using population and monthly average light output to classify village electrification status. Min et al. do not provide explicit classification accuracy metrics or precise definitions used for village electrification (Min et al., 2013). Definitions of electrification are paramount to understanding electrification status and planning effective interventions. Two related considerations render the Min et al. methodology inadequate for detailed electrification planning: the aggregated village-level nature of electrification status presented and the use of a binary measure for village-level electrification status. Usually, villages in the developing countries under consideration are not simply 0% or 100% electrified; even connected villages can have large populations without energy access. Ultimately, further processes for disaggregation are required to produce building-level estimates.

Lee presents experiments with multiple model types for building-level and ~1 km resolution in the estimation of electrification status. The author compares results for models based on logistic regression (LR), Gaussian Processes (GPs), and probabilistic graphical models (PGMs) for case studies in Uganda. The GPs presented demonstrate improved performance metrics relative to LR approaches due to their ability to capture spatial correlations in electrification status; however, Lee hypothesizes that LR approaches may be able to better incorporate multimodal data and generalize to regions outside of those close to direct survey measurements. Lee goes on to introduce ongoing work on the hierarchical beta model, a PGM that promises to combine multimodal and multiscale features (such as aggregate census statistics, existing grid information, population density, nighttime lights values, and satellite image features) in addition to capturing spatial correlation (Lee, 2018).

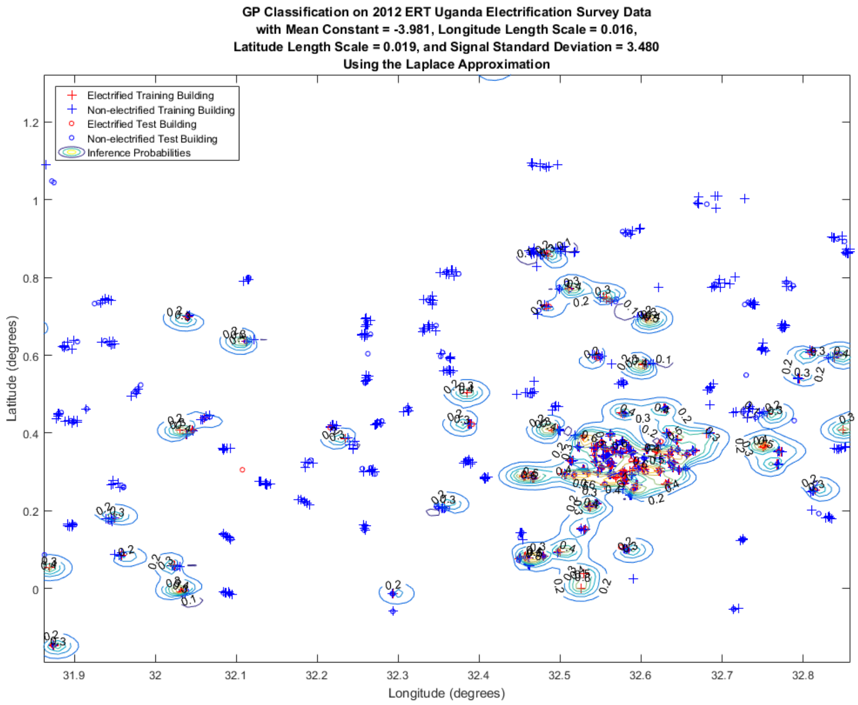

Figure 8. GP results corresponding to the survey data, zoomed into the capitol city, Kampala. Source: (Lee, 2018).

Figure 8 shows example output for a GP classifier trained with survey data and zoomed into Uganda's capitol city, Kampala. Model specifications are given in (Lee, 2018). Such electrification probability maps can be compared to expert elicitations and used to inform master planning efforts. For use with REM, we can use probabilistic models such as GPs for electrification status estimation by simulating electrification data sets. This is done by treating estimates as biases for Bernoulli random variables. By essentially "flipping coins" for every household in an area of interest, representative electrification landscapes are generated that can be fed into techno-economic analyses.

3.3.1.4 Combining information from different data sources

Sometimes requisite information for areas in need of electrification is inaccurate, outdated, or not available. Examples include poor quality imagery due to blurred images, clouds, or other artifacts. Even if the quality is acceptable, readily available imagery may be outdated and not reflective of the situation on the ground. Therefore, it is necessary to collect information from different data sources to corroborate the validity of buildings data and to make estimations. Relevant features include population and population density, which are values that must correlate with the number of buildings and its distribution.

Since image-processing algorithms can be adjusted in sensitivity to detect a slightly higher or lower number of buildings, if the results do not match expected population values, it is possible to adjust sensitivities to enforce better matches.

If buildings cannot be identified using images but the population and the boundaries of a village are known, it is possible to estimate building positions by assuming a uniform distribution. Figure 9 shows the difference between real building locations and estimated building locations for the village of Zugu in Nigeria.

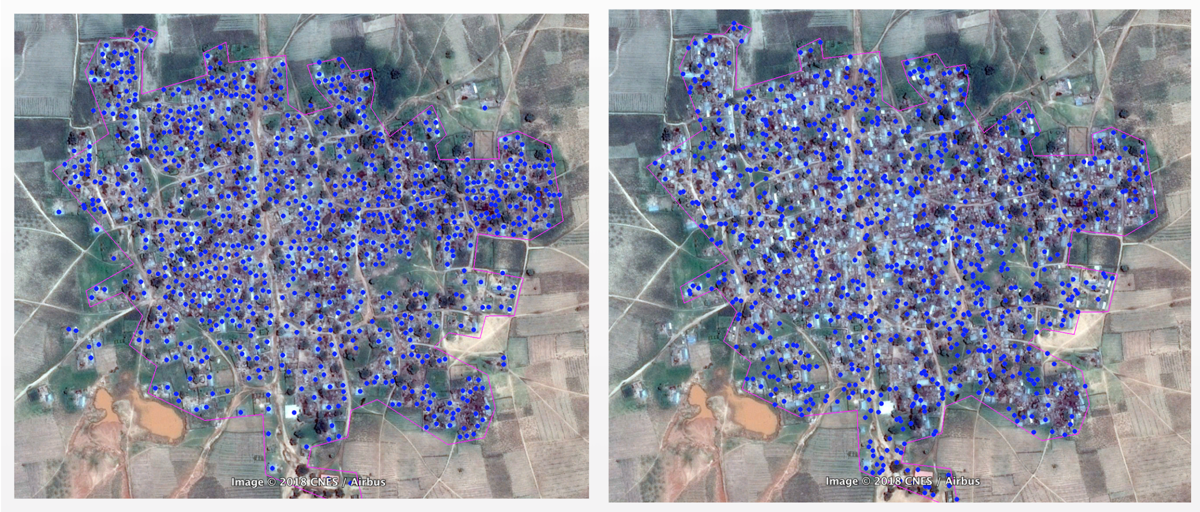

Figure 9: The left image shows manually annotated coordinates of all buildings, visualized using Google Earth. The right image shows randomly generated buildings, distributed within the polygon line that delimits the boundary of Zugu (Rungan-Gazo) in Nigeria.

Comparing actual building locations with uniform building distribution (randomly generated and distributed) for a given village of uniform density, has shown similar results in terms of electrical network design. In one example, the difference of the total electrification cost between the case with actual building locations and the case with random building locations was less than 1%. For the same number of buildings modeled, there is only a small difference in the length and type of the power lines prescribed, but the costs for the generator and transformer are the same. These preliminary results suggest that in areas with poor quality satellite imagery, it is possible to estimate building location if the population is known. In addition, if there are estimations of population growth, it may be possible to simulate building locations in a similar way, hence being able to obtain the best future electrical grid for regional planning purposes. Nevertheless, when it comes to real implementations, the design of the local network for each cluster has to be based on the correct location of each building to be electrified.

Population data can typically be obtained from the region's most recent census as long as it may be considered accurate and up-to-date. It is also possible to obtain future population estimates from demographic studies. However, the most valuable information for building location is population density that can be obtained from several GIS providers. The LandScan Global Population Databases, was developed at the Department of Energy's Oak Ridge National Laboratory. It is a raster database that covers the whole world with population information since year 2000. As of 2016, LandScan contains population counts at 30 arc second resolution (ORNL, 2018). Another useful raster database is the High-Resolution Settlement Layer (HRSL), described in Section 3.3.1.1 (HRSL, 2018).

HRSL provides estimates of human population distribution at a resolution of 1 arc-second (approximately 30m). In the countries for which HRSL data is available, it is possible to obtain relatively accurate customer locations by randomly distributing them in accordance with corresponding population density estimates.

3.3.2. Demand profiles for each type of building / load.

One of the most important inputs to an electrification model is expected customer demand. In the case of REM, customers are categorized into broad archetypes with unique hourly consumption trends. The demand of each archetype is modelled either as a single power utilization pattern or as a linear combination of several patterns (see section 3.2.2).

The decision to use a linear combination of demand patterns has two primary reasons:

1. There is limited information available on how specific types of customers expect to use (or have previously used) electricity. As such, linear manipulation of data can be a useful method of extrapolating reliable load information to different groups. For example, an assumption can be made that large households consume three times as much as small residential customers.
2. To reduce REM's computation time (See sections 3.1 and 3.2.2). During the clustering process REM calls on a lookup table that includes a set of typical electrical generation mixes. The model will then interpolate capacities from the table and design the future electrification system. To simplify this process only a set number of demand profiles (i.e. patterns) are allowed. Linearly combining these patterns allows for more granular demand projections.

Each demand pattern is characterized by several *demand samples*. The samples provide alternative consumption chronologies to account for the uncertainty in customer usage, for each profile (see section 3.2.2). Each demand sample specifies two consumption series, critical and non-critical electricity demand. The series consist of 8760 values, for every hour in a year.

Demand profiles identify the minimum amount of electricity needed to satisfy the customer's load at 100%, 24 hours a day. However, REM is not constrained to meet all the demanded capacity. Instead, it optimizes for cost and therefore may choose to reduce reliability of the electricity to avoid significantly scaling system components.

User-defined costs of non-served energy (CNSE), for critical and non-critical demand, successfully translates these supply failures into social costs. REM also allows users to input supply patterns, as a means of representing power/time supply limits possibly imposed by generation or distribution contracts.

Accurately modelling demand profiles is complex, and it is tackled in several ways by REM. The following sections will go into more detail.

3.3.2.1 Demand profile Methodology based on Appliance Utilization

One way to formulate demand patterns for a given profile is by calculating the power of the appliances expected to be used (Ellman, 2015). Random combinations of the appliances is necessary to generate a representative, unbiased set of demand samples. It should be noted that demand samples are pre-computed, and act as an input to REM. See Figure 10 for an example of consumption values by appliance.

How people consume electricity varies as temperatures change and as sunlight fluctuates. Therefore, climate data is also factored into expected hourly demands. Finally, the profiles are interpolated across an entire year's worth of usage.

Appliance	Critical (1=yes, 0=no)	Average # Owned	Power (kW)	Probability of Ownership	Average Daily Duration (hours)	Average Daily Duration Criteria		Enabling Criteria		Potential Time Range	Appliance Variability
Light 1	0	2	0,015	1	5			Irradiance less than	0,05	See table below	0,2
Light 2	1	2	0,015	1	5			Irradiance less than	0,05	See table below	0,2
Light 3	0	2	0,015	1	5			Irradiance less than	0,05	See table below	0,2
Fan	0	0	0,07	0,26		Temp greater than	32,5	Temp higher than	29,5	NA	0,2
TV-night	0	0	0,053	0,26	5					See table below	0,2
TV-day	0	0	0,053	0,26	1					See table below	0,2
TV standby	0	0	0,007	0,26						NA	0,2
Daily Variability	0,2										

*Translate Potential Hours to Hours Appliance Will NOT be on

Hours Not on — *note: hour 1 of the day should start at 0 (24 hours, starting from hour 0 to 23)

	Light1	Light2	Light3	Tvnight	Tvday
1	0	0	7	0	15
2	1	1	8	1	16
3	2	2	9	2	17
4	3	3	10	3	18
5	4	4	11	4	19
6	5	5	12	5	20
7	6	6	13	6	21
8	7	7	14	7	22
9	8	8	15	8	23
10	9	9	16	9	0
11	10	10	17	10	1
12	11	11	18	11	2
13	12	12	19	12	3
14	13	13	20	13	4
15	14	14	21	14	5
16	15	15	22	15	6
17	16	16	23	16	7
18				17	8
19				18	9
20					10
21					11
22					
23					
24					

Figure 10: File defining the random use of appliances

During the analysis of appliance usage, the following factors are considered:

- Critical: Set at 1 if the appliance is critical for daily use, or 0 otherwise.
- Average Number Owned: Average number of appliances that customers in each profile are expected to own.
- Power (kW): The active power needed by each appliance.
- Probability of Ownership: Specifies the probability that a customer in the respective demand profile owns the appliance.
- Average Daily Duration (hours): Average number of hours the appliance is typically used for.
- Average Daily Duration Criteria: This field is an alternative to “Average Daily Duration (hours)”, and only one can be used at a time for each appliance. The property sets constraining criteria on when an appliance would be on.
- Enabling Criteria: The appliance will not be used if the condition indicated in this field is not satisfied. For example, data in the first table implies that the fan will not be used if the temperature is lower than 29.5 ºC.
- Potential Time Range: Indicates whether time-of-day usage will affect the demand profile and/or what time during the day the appliance is expected to be on. If it is set at “NA” then it has no influence on demand profiles. Otherwise, it will reference “table below” which will indicate the hours of the day an item will off.

For example, Light1 will not be used between midnight (00:00) and 16:00. Since the field average daily duration of the first table indicates that Light1 is used an average of 5 hours a day, these 5 hours must lie between 16:00 and 00:00.

- Appliance Variability: The variation in the hours of use of the appliance.
- Daily Variability measures how variable the overall demand is over multiple days. Hence, this field corresponds to variations in the number of hours of all activities, rather than a particular one.

Figure 11 provides an example of residential demand including lighting, television, and fan usage (Ellman, 2015). The input sources include US census data, peer-reviewed studies, surveys, and demand data captured on the field.

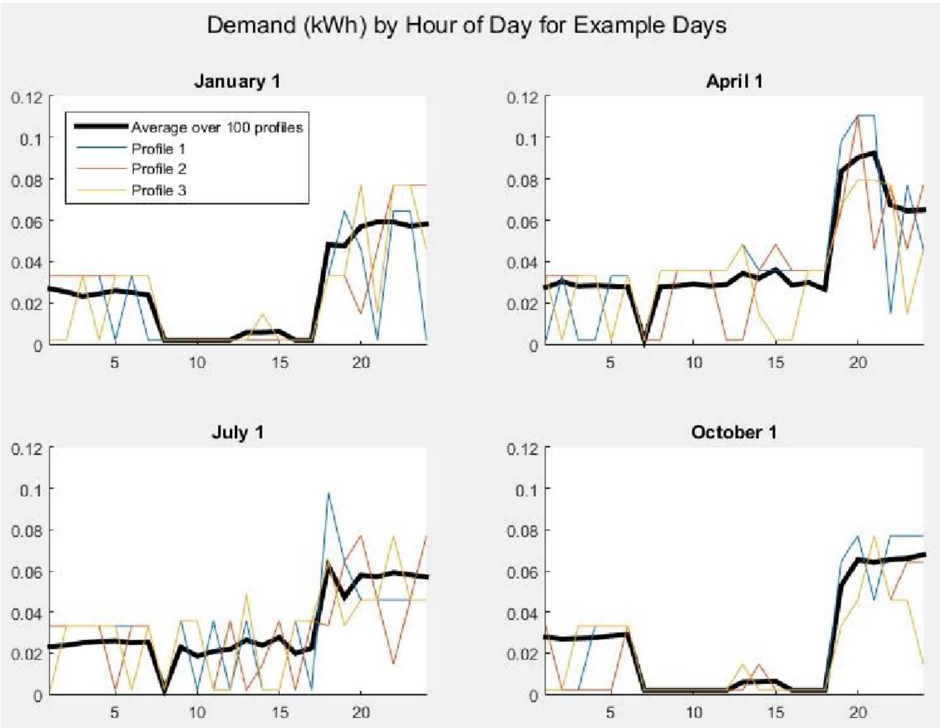

Figure 11: Example of demand samples based in the use of appliances (Ellman, 2015)

3.3.2.2 Demand profiles from external sources

When field survey data on expected power consumption and appliance usage is limited, trivial, or not available, commercial and feeder records can prove useful at estimating natural demand (demand of similar customers in similar socio-economic and geographic situations). Some of the sources used were:

- **Commercial Information:**
  - Metrics available include: Average energy consumptions per month or year, peak load, and installed limiters for different customer types.
  - When information about the nature of demand is available (e.g. classification of households with different peak demand levels, community and productive uses), different hourly load patterns per customer type can be calculated as an input for REM.

- **Feeder information:**
  - Distribution companies sometimes have hourly records of the energy supplied by different feeders. The data is often supplemented with the number (and archetype) of customers per feeder. These records can then be disaggregated downstream to the individual household or commercial level, by assuming similar customer characteristics.
  - It is especially helpful to have information about dedicated feeders for agriculture (e.g. irrigation pumps in India), commercial (e.g. shopping malls in Colombia), and industrial customers. This information would help delineate load patterns between more specific, special case customer types.
  - Feeder information is also useful to determine the reliability of the supply, and how it relates to the type of customers on the feeder.

For planning purposes, decision makers may decide to deviate from using the natural or expected demand for certain types of customers. For instance, they may decide to plan for a certain target or tier either above or below the natural demand. As an example, in the Rwanda National Electrification Plan, relatively isolated low-income customers will be provided with low-capacity solar kits, whereas other grid or mini-grid connected customers might get their natural demand met (or what they can afford, depending on the applicable tariff).

With REM, or any electrification model, developing a reliable and comprehensive demand profile is critical to understanding hourly, daily, and seasonally load variations. This is especially useful when calculating the necessary generation capacity of a specific town or region. With REM, a realistic customer-level demand representation means stronger analysis on how to most efficiently (and cost effectively) cluster customers.

3.3.3. Topography and administrative divisions.

Once acceptable input information is provided, REM and RNM can make adjustments to the network costs, in accordance with the altitude, the ground slope, and by avoiding forbidden zones within a particular orography. These adjustments can be then accounted for in the network routing and clustering algorithms.

The objective function that optimizes the layout and the size of the power lines is guided by the net present value of investment, as well as preventive and corrective maintenance costs. Apart from other concepts -such as the cost of the equipment required to improve the system reliability, and the cost of ditches, façades and posts, capacitors and voltage regulators- the model considers unitary investment and maintenance costs that depend on the type of power line. Two penalty factors that capture the cost of changing altitudes and crossing the so-called forbidden zones (i.e., zones with a particular orography such as lakes, rivers or forests) multiply the length of the line, which then appears to be costlier. Two input files are required to calculate these two penalty factors: the altitude raster and the zone-definition polygon files.

The altitude penalty factor depends on the ground sloping. The model can accept altitude information in Environmental Systems Research Institute (ESRI) ASCII raster format[1]. The file

[1] A description of this format can be found at (ASCII raster format)

stores topographic data information in a numerical matrix where each pixel indicates the altitude of the raster map, in a manner that allows rebuilding the orography and elevation of the terrain. The basic information to enable reconstructing the raster map includes the number of pixels in rows and columns, the coordinates of the southwest corner in a predefined geographical system, the size of each pixel, and the default elevation value when the elevation is not available.

The National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) provides digital elevation data covering all countries. It is available in either 30-meter[2] or 90-meter resolution from the United States Geological Survey website (USGS). An example of the 30-meter SRTM data obtained for the country of Rwanda is displayed in Figure 12. These data can be downloaded in TIFF format, projected into the appropriate Universal Transverse Mercator (UTM) coordinate system, and converted to ESRI ASCII raster format using a GIS software such as ArcGIS.

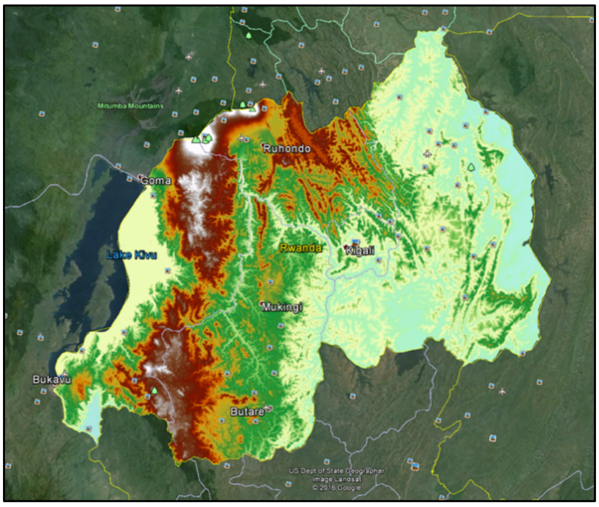

Figure 12: NASA Shuttle Radar Topography Mission Rwanda Altitude Data – 30m Resolution

The forbidden area factor depends on the existence of geographical features, such as lakes, wetlands, national parks or other designated zones. RNM and REM use a file that contains a set of polygons. Each polygon is defined by a set of coordinates preceded by a header where the user can specify the penalty multipliers for the zone. Huge multipliers (for instance 10^6) may be used to completely avoid penalized areas in network routing decisions, while moderate multipliers (for instance 1.5) may account for realistic extra costs.

The forbidden zones correspond to specific features of the terrain, which can be obtained from international or local databases. For example, the lakes in Rwanda are available in ESRI shapefile format[3]. These terrain features, as well as other designated zones, can be input as forbidden zones, so that the model tries to avoid them in the network design process. The outline of the countries can also be used to define the forbidden zones. This is especially relevant if the country has a coastline. See for example the case of Nigeria in Figure 13. The REM/RNM input files of the forbidden ways-through can be derived from ESRI shapefiles using a converter and specifying the penalty factors.

[2] It should be noted that the spatial resolution of the 30m and 90m data is actually one and three arc-seconds, respectively, which is approximately 30 (90) meters at the equator.

[3] See The Humanitarian Data Exchange (https://data.humdata.org/dataset/rwanda-water-bodies). Source: the Rwanda National Institute of Statistics.

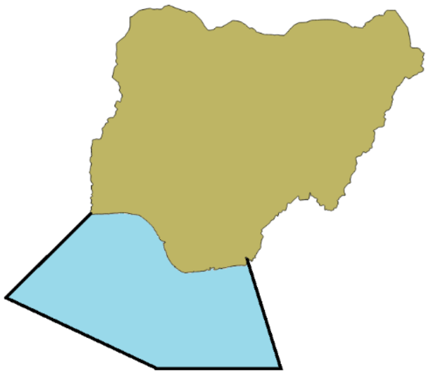

Figure 13: Forbidden way through in Nigeria corresponding to the coastline.

The impact of topography and penalized zones in the network topology is shown in Figure 14. Note how the layout of the network changes dramatically when considering forbidden and penalized zones.

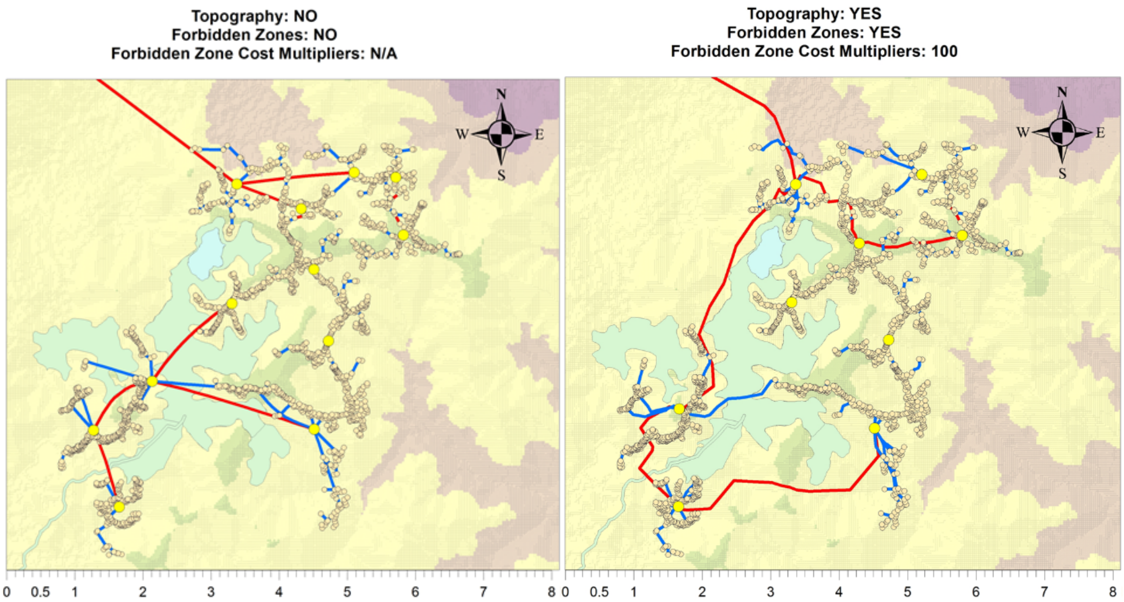

Figure 14: Influence of altitude and forbidden zones in the network topology (Drouin, 2018)

In some cases, it is necessary to consider the administrative boundaries in the clustering process. For instance, REM can be forced to obtain independent electrification solutions for different administrative regions. This requires delimiting them with polygons, which are used in the model to split the whole problem into smaller sub-problems, each of them processed and analyzed independently, even using parallel computing. For this purpose, the model requires as input data the polygons that define the boundaries of the administrative divisions. This data has to be obtained for the specific country under study using local databases. For, example Figure 15 shows the administrative divisions in Rwanda.

Figure 15: Rwanda Administrative Provinces

3.3.4. Existing distribution network.

REM considers three different electrification modes: stand-alone systems, mini-grids, and grid extensions. Unlike the first two modes of electrification, grid extensions require REM to both model and *interpret* already existing infrastructure; specifically, the location and capacity of connected transmission and distribution lines.

Due to the well-known complexity and innumerable constraints involved in electrical grid design, a few simplifications were included when creating REM and RNM. For instance, both models (REM and RNM) can apply only one voltage value to each voltage level in the distribution network (i.e. HV, MV and LV). Existing electrical grids, however, may use several voltage levels in different feeders, which is impossible to model on RNM/REM. So three predefined voltage levels are used to homogenize the current grid and simplify model computation. For instance, medium voltage lines (MV) may be set at 3-phase 12.47 kV, and low voltage lines (LV) may be set at 3-phase 0.4 kV. As mentioned in section 3.2.7, the use of diversity of voltages, or a different number of phases, must be emulated using equivalent components.

The model also requires its user to explicitly define where the potential connection (i.e. extension) points are. In our case this only includes the MV nodes and line segments. In general, the per-unit wholesale cost of energy ($/kWh) at these connection points is different for each one, if there is information to distinguish the differences in any required reinforcement infrastructure. The cost of these extra investments is not ignored, but it is assumed to be proportional to the amount of energy provided.

To characterize the existing grid, the user can obtain the electrical details automatically from databases (open sourced or otherwise), or can manually draw it through the inspection of images and line diagrams. In REM, the existing MV network is represented by a set of line segments, each one defined by two coordinates.

REM uses the candidate MV connection points to evaluate the network cost (and layout) of a grid-extension solution, for a specific cluster of consumers. In order to do so, REM chooses a subset of representative MV points –adequate for the particular cluster- as potential connection points; then REM submits the problem to RNM, which is free to use any of them to provide an optimized layout.

Each MV segment is allocated an energy price, in $/kWh, which could depend on the supply connection point to account for differences in the locational price of delivering electricity. Although in RNM the price of delivering electricity is only considered to compute the cost of energy losses, this price is obviously critical in REM decisions.

Each MV segment also exhibits a specific reliability level. The reliability level is inputted as a vector of 24 elements that characterizes the hours of a representative day. The reliability level must be within the range [0, 1], where this value indicates the fraction of demand that is supplied during that hour. ‘0’ means that no demand can be supplied, while ‘1’ means that all demand is supplied. The reliability of feeders can be either based on actual measurements or estimated through customer surveys.

3.3.5. Catalog of components: networks and generation sites.

REM is a cost-driven tool that makes use of detailed technical models. One of the highest contributing factors to electric grids is the purchasing, operation and maintenance of their assets (electrical equipment). Moreover, technical constraints include capacity and voltage drops in networks, and the hourly operation limits of mini-grid generation sites. As such, it is important to both accurately identify the necessary equipment and size them as needed.

3.3.5.1 Catalogs of network components

These input files have been already introduced in section 3.2.7, but it is worth recalling the following points:

- Lines and transformers are described in terms of electrical parameters (power, impedances) and cost parameters (investment, maintenance).
- Separate catalogs can be defined for grid extensions and mini-grids. This is a strategic decision, since the advantages of grid-compatible mini-grids must be weighed against the use of low-cost isolated networks.
- REM assumes standard 3-phase networks with only three voltage levels (HV, MV, LV). The use of other voltages or number of phases must be emulated using equivalent components in the catalog, in which the main parameters are kept (costs, power capacity, voltage drop, losses) while impedances are replaced for consistency.

The data in the catalog has to be verified so that economies of scale are respected. This is mandatory to avoid difficulties in REM’s mathematical optimization processes. The components must be ordered by increasing capacity, and the cost/capacity ratio must be decreasing. Care must be exercised, since mixing products from different vendors or technologies may be inconsistent.

Figure 16 shows portions of a line-catalog and a transformer-catalog, which exhibit the level of detail handled by REM.

name	R	X	Phases	I_rated	I_OL	V_rated	FR_min	FR_mean	FR_max	C_inv	C_prev	C_corr
Weasel	1.16	0.33	3	129	1.2	33000	0.133	0.133	0.133	5562.7	700	2870
Ferret	0.87	0.32	3	155	1.2	33000	0.133	0.133	0.133	6676.9	700	2870

name	S_nom	phases	V2	V1	PL_0	R_LV_DC	max_outl	C_outlet	FR_min	FR_mean	FR_max	C_inv	C_prev	C_corr
SEI1_V	3150	3	11000	33000	7	0.317	10	21000	0.003	0.003	0.003	46953.27	27000	2200
SEI2_V	5000	3	11000	33000	10	0.2	10	21000	0.003	0.003	0.003	74529	27000	2200

Figure 16: Examples of catalog components: lines and transformers

Experience shows that getting realistic and feasible catalogs requires interaction and post-processing. External data are usually incomplete and inconsistent. Fortunately, most of the required parameters can be estimated, or even re-used from other projects. This is the case of typical impedances, failure rates or maintenance cost figures. However, a few parameters must be carefully adjusted with the client in order to obtain meaningful results. These are investment cost, power capacity, voltage, and number of phases.

3.3.5.2 Catalogs of generation-sites components

These files have been already described in section 3.2.8; the following remarks are made here:

- The standard mini-grid is AC-3-phase powered. Solar kits in DC are modelled separately and considered only in the final electrification phase of the algorithm.
- The local generation site has a flexible structure. Its maximum complexity is shown in Figure 5: diesel generator, PV panel, battery, charge controller and inverter. Five simpler designs are allowed: a) only a diesel generator; b) only a PV panel; c) PV + diesel; d) PV + battery; e) diesel + battery.
- For PV panels and batteries, only two options for each (defined by their technical characteristics and size) are allowed in the current version of REM, one more adequate for small standalone systems and the other one for large generation sites.

The above-mentioned requirement about economies of scale (as in lines and transformers) also applies to diesel generators, charge controllers and inverters: components must be ordered by increasing capacity, and the cost/capacity ratio must be decreasing. Efficiency should increase as well with size, or at least it should not decrease.

Figure 17 shows portions of a diesel generator catalog and a battery-catalog.

name	pMax	invCost	installFrac	OMfracost	OMpuHRS	lifetime	pMin	fuel_0	Eff_fuel_025	Eff_fuel_05	Eff_fuel_075	Eff_fuel_full	startupFuel	startTime	stopTime
G2	5	3200	0.8	0.05	25	35000	0.5	0	0.5	0.442	0.408	0.385	0	0	0
G3	15	9000	0.8	0.05	25	35000	0.5	0	0.45	0.408	0.385	0.371	0	0	0

type	energy	cost	installFrac	OMfraccost	OMpuHRS	LT ThroughPut	Imax	I_disch_max	Vnom	eff_batt_d_c	SOCinit	SOCmin	SOCmax	EOLcapac	c	k
VIS_CP12240D	0.284	60	0.2	0.01	5	103	9.6	300	12	0.894	0.4	0.4	1	0.8	0.325	2.38
TROJ_T105	1.38	150	0.2	0.01	5	845	11	NA	6	0.922	0.5	0.5	1	0.8	0.281	1.85

Figure 17: Examples of catalog components: diesel generators and batteries

As it happens with lines and transformers, getting realistic and feasible catalogs for generation components requires interaction with local agents and post-processing. It is also true that external data are usually incomplete and inconsistent.

Generation components may in general be adapted from other projects. However, in the generation-set design problem the clients may demand specific requirements that, in practice, differ much from one another. Some of them can be implemented via generic configuration parameters, but other design criteria require code adaptations. For instance, in some projects generation is required to be modular, using only some number of standardized sets; this apparently simple requirement is not compatible with the basic optimization logic used in REM, because:

- It requires the use of special catalogs and formats,
- Discrete sizes cause local optima in the REM standard clustering algorithms; the only way to avoid them is adapting the clustering logic to the fact that economy of scale in generation comes in discrete jumps (“magic” sizes of clusters that fit perfectly with generation modules).

3.3.6. Cost drivers and financial models.

REM considers direct monetary costs and indirect societal costs in the economic evaluation of electrification plans.

3.3.6.1 Direct Monetary Costs.

The direct monetary costs include both initial investments and on-going expenditures. The costs are categorized as investment costs, operations and maintenance costs, management costs, and energy cost. To account for the time value of money, REM discounts future expenditures based on the appropriate discount rate for each technology. By allowing different technologies to be discounted with independent discount rates, REM accounts for the diverse ownership structures and risk profiles that are possible in the studies to be performed with the model. For instance, utility-owned grid extension projects should have a lower discount rate than privately-owned solar home systems.

REM is a "static optimization planning model", which determines the minimum cost solution for just a future snapshot situation, i.e. one year in the future. Due to the wide range of equipment lifetimes used in the electrification space, an annuity for that future year is computed for each technology. This allows to jointly account for shorter-lived products, such as solar home systems, and assets with longer economic lives, like lines and transformers in the distribution networks.

A constant perpetuity assumption is used to convert from Present Value PV to Annuity:

$$Annuity = PV \cdot r$$

For expenditures occurring on a non-annual basis, the expenditure is converted to a yearly annuity, where C is the periodic expenditure, r is the discount rate, and L is the period:

$$Annuity = \frac{C \cdot r}{(1 - (1 + r)^{-L})}$$

Direct monetary costs include investment, O&M, management, and energy costs:

- Investment costs, or CAPEX, are determined directly from the system design and associated cost catalog. For grid extension, this is often dominated by the cost/km of the distribution network, whereas for mini-grids, the $/kW for solar PV and $/kWh for battery storage are often the most significant components of the total cost of supply. As mentioned above, these capital expenditures are converted to annuities to compare projects in the "static optimization" REM.
- Each equipment type is assigned an annual operational and maintenance cost (O&M) based on the local equipment characteristics and necessary expenditures to maintain equipment in working condition. For distribution lines, this is defined by ($/km)/year, but for transformers, batteries or diesel generation sets, this is defined simply as $/year for a given piece of equipment.
- Annual management costs differ by system type and size due to the nature of different pieces of equipment and different business structures. When modeling the management cost for grid extension projects and solar home systems, REM assumes that economies of scale have been reached, and the marginal management cost of each additional customer is uniform. When considering the management cost

associated with mini-grids, REM assumes that each mini-grid will have some fixed management cost, plus a monotonically decreasing marginal cost per additional customer. In this way, the model acknowledges the economies of scale associated with mini-grids of increasing size.

- Direct energy costs happen in grid extension projects and mini-grids with diesel generation. For grid extension projects, the cost per kWh of energy is the wholesale electricity price when delivered at MV level (which includes the true price of energy at wholesale level, plus transmission and HV distribution costs). REM currently assumes a constant cost of electricity regardless of hour-of-day or time-of-year, and regardless the amount of energy demanded, although that cost can be different depending on the connection point location. For mini-grid systems with diesel generation, the price of diesel fuel is the only energy cost.

3.3.6.2 Non-monetary Costs.

The least-cost optimization performed by REM also includes non-monetary costs. The main societal cost is the Cost of Non-Served Energy (CNSE), which is associated with the reliability of supply. REM imposes this penalty on a per-kWh basis for every unit of energy demand that is not supplied. This penalizing factor ensures that system reliability is properly accounted for, while making sure that supply does not become prohibitively expensive, since the direct monetary costs quickly grow with higher reliability levels.

A single value of CNSE cannot capture the diversity of situations of supply failure, as perceived by customers with different needs and at different times. As a reasonable approximation to this complex reality, REM distinguishes between critical and non-critical loads for all customers, and applies a different value of CNSE to the curtailment of critical and non-critical demand. Critical and non-critical demand profiles are specific for each type of customer and demand pattern, although the related penalties (the two values of CNSE) are currently the same in REM for all the customers. Determination of the appropriate value for CNSE is a difficult task, which would require extensive and very well-designed surveys of the involved customers. Fortunately, REM allows playing with the values of CNSE until the model delivers reasonable combinations of cost and reliability of supply.

As mentioned in section 3.2.2, REM allows the definition of supply patterns. These are supply limits for demand patterns, in terms of maximum power and time intervals (different for grid extensions and mini-grid solutions). This allows modelling:

- Power limiters, i.e. devices installed at the household connection point that prevent power consumption to exceed a threshold established by contract
- Low-cost supply contracts that cover only partial electricity needs.

A different CNSE penalty is defined for the demand that is not served due to supply limitations, to account for its equivalent social cost. This penalty should be lower than the critical and non-critical ones, since the lack of supply is known in advance by contract.

3.4. REM technical procedures.

This section describes the main procedures implemented in REM to solve the electrification problem.

3.4.1. Mini-grid generation design.

A critical aspect of a rural-electrification planning problem is the design of the off-grid generation systems that may be part of the final electrification solution. Those designs depend on demand, available technology, and local conditions such as the cost of fuel and the hourly solar irradiance.

REM assumes that mini-grids have centralized generation and operate in islanded mode. The adopted general architecture for any off-grid system in REM was shown in Figure 5. It is a fairly common design and meets the requirement of being able to provide an AC output, which will be necessary in case of a hypothetical connection to the main grid. REM does not include all the components in every generation design. For instance, if a mini-grid has only a diesel generator then converters and inverters will not be included.

3.4.1.1 The generation sizing algorithm.

The algorithm that REM uses to determine the generation design of a mini-grid is a variation of the Hooke and Jeeves algorithm (Hooke and Jeeves, 1961) which starts by picking an initial point in the multidimensional space of the mini-grid design variables. Then, the search continues by calculating the value of the objective function (costs plus penalties) for several points around the initial point, and moving from the initial point along the minimum-cost direction. For each candidate point in the search space (with as many dimensions as design variables for the mini-grid), REM performs an annual simulation of the operation of the mini-grid, adopting some generation dispatch strategy, and calculates the total cost of that point including investment and operation costs plus a penalty for the non-served energy.

This algorithm moves in a tridimensional search space where the dimensions are the diesel generator capacity, the total capacity of the solar panels and battery capacity. REM sizes the remaining components of the design afterwards. The first step of the sizing algorithm is to establish the boundaries of the search space, estimating the maximum and minimum possible value in each of the three dimensions.

The possible values that the diesel generator could take in the search space are provided by the user in the generation catalog and hence the diesel axis is not necessarily equally spaced. However, the possible values that the solar panels and the batteries could take in the search space are given by combining several units or a single solar panel or battery in a row. This implies that the points along the dimensions of solar and batteries are equally spaced.

Moving from a diesel generator to the immediately bigger or smaller one could produce significant variations of capacity (for example, from 5 kW to 10 kW). In order to avoid local minima, the algorithm that REM uses is based on a master-slave decomposition where the master problem controls the diesel axis, and the slave problem moves inside a solar-battery plane with a fixed diesel capacity and an initial search point that the master level provides. This nested optimization decomposition, which is shown in Figure 18, has been successfully used in problems of different nature (Prada y Nogueira, 2017; Liu and Zhang, 2014).

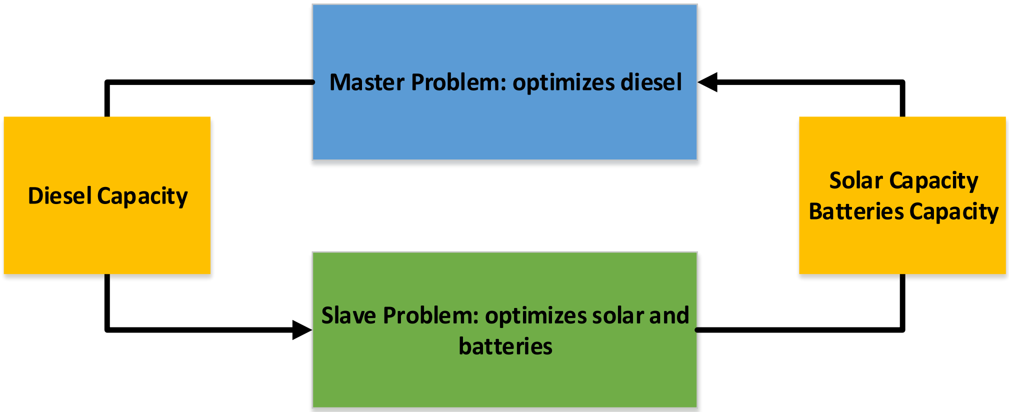

Figure 18: Master-slave decomposition

Some components of the cost of the candidate designs depend on the mini-grid operation, such as fuel, replacements, and non-served energy. These terms are estimated by simulation, using for instance the "load following" dispatch strategy (Dennis Barley and Byron Winn, 1996). For a given generation design, the load following strategy uses first the solar energy to meet the demand and, if the battery is not fully charged, the remaining solar energy is used to charge it. If there is not enough solar energy, and the battery is not fully discharged, then the battery is used to meet the demand. Finally, if there is still demand that cannot be met, the load following strategy either uses the diesel generator or allows some non-served energy (least-cost decision, according to the penalties for non-served energy).

There are other ways of dealing with the generation sizing problem. Instead of using this heuristic approach, the investment and the operation problems can be formulated as a classic optimization problem that considers the generation design and the dispatch at the same time. This formulation has already been implemented (Moretti et al, 2018) with satisfactory results.

3.4.1.2 The look-up table.

In a large-scale rural electrification planning problem, the task of calculating accurate generation designs for all the candidate mini-grids is computationally unfeasible. This implies that the iterative application of a generation sizing tool such as HOMER would not work and there is a need of finding a new methodology that balances accurate calculation with a moderate amount of computation time.

What REM does to solve this problem is to calculate only a few generation designs for a representative number of candidate mini-grids and, if it needs information of another design, the model will obtain it using multi-linear interpolation. Figure 19 shows a small rural electrification planning problem that we will use to illustrate this concept. There are 32 residential consumers in this problem with the same demand profile.

Since all the consumers have the same demand, there are also 32 candidate off-grid systems with different aggregated demands (those with 1, 2, … 31, 32 consumers). Instead of calculating these 32 generation designs, which would be a feasible strategy for this toy example but not for a large-scale problem, REM could calculate the generation designs related to 1, 2, 5, 15 and 32 consumers. If it needs information of a generation design with – for instance- 25 consumers, the model will interpolate the values, using the data from the designs with 15 and 32 consumers.

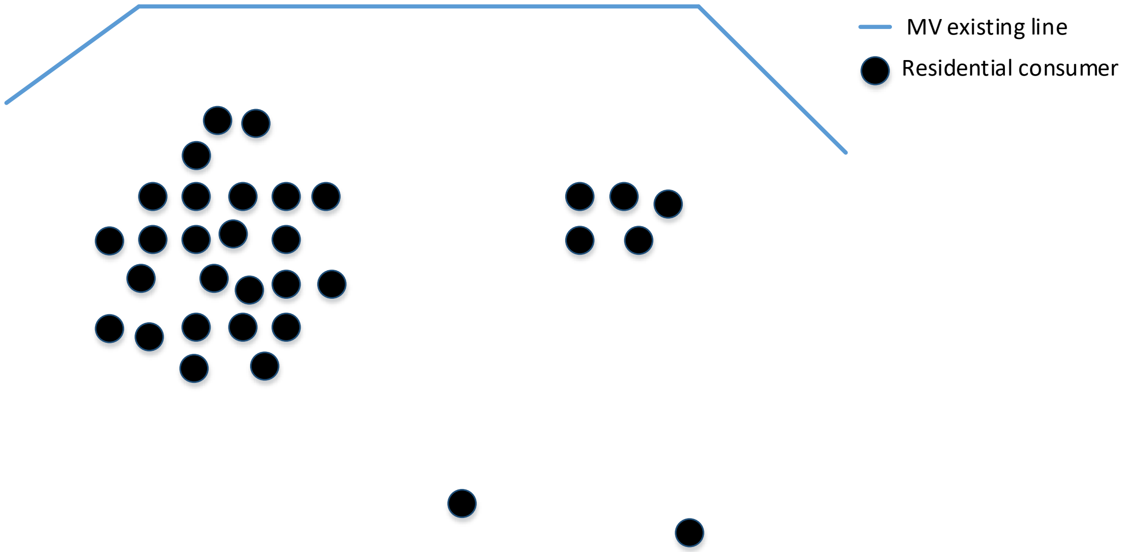

Figure 19: Electrification problem example

In this example, the look-up table would have a single axis with five representative points related to residential consumers. Things, however, are more complicated if we introduce other types of consumers, such as productive loads or bigger households, with their corresponding demand profiles. Specifically, adding a new consumer type to the look-up table implies adding one more dimension in the space of consumers, and the total number of generation designs that REM would need to calculate could be significantly larger.

3.4.1.3 Dealing with multiple types of consumers

The number of customer types that REM can process limits the look-up table approach. A case example with five different consumer types would imply a penta-dimensional look-up table that would require computing too many points. In order to overcome this limitation, it is important to realize that generation designs are related to the aggregated demand of candidate mini-grids, and not to specific combinations of consumer types. This implies that it is worth associating the axes of the look-up table with “demand patterns” instead of customer types. By doing so, REM can operate with a number of customer types that is higher than the number of axes of the look-up table, as far as the demand of any customer type can be expressed as a linear combination of a set of “basic” demand patterns.

For example, we could have two different types of residential households – big and small – and assume that the demand of a big household is five times the demand of a small household. Then REM could have one demand pattern related to the small household profile and the point “5” of the look-up table could be either five small households or one big household, since the demand is the same in both cases.

It seems logical to explore this idea, using dimension reduction techniques that synthetize a large number of demand profiles related to customer types into a few basic demand patterns associated with axes of the look-up table. Both the basic demand patterns and the linear combinations are specific inputs to REM. Patterns may be defined directly by the user, using problem-domain expertise, or computed separately with optimization algorithms.

3.4.2. Clustering.

The goal of the clustering process is to determine which consumers should be electrified together (i.e. with the same system) and based on what the most efficient way to electrify them is. Evaluating all the possible combinations would be computationally unfeasible in large-scale problems.

REM uses a Delaunay triangulation to obtain the potential connections among consumers. This procedure has already been used in clustering algorithms related to distribution networks (Mateo Domingo et al., 2011; Peco, 2001).

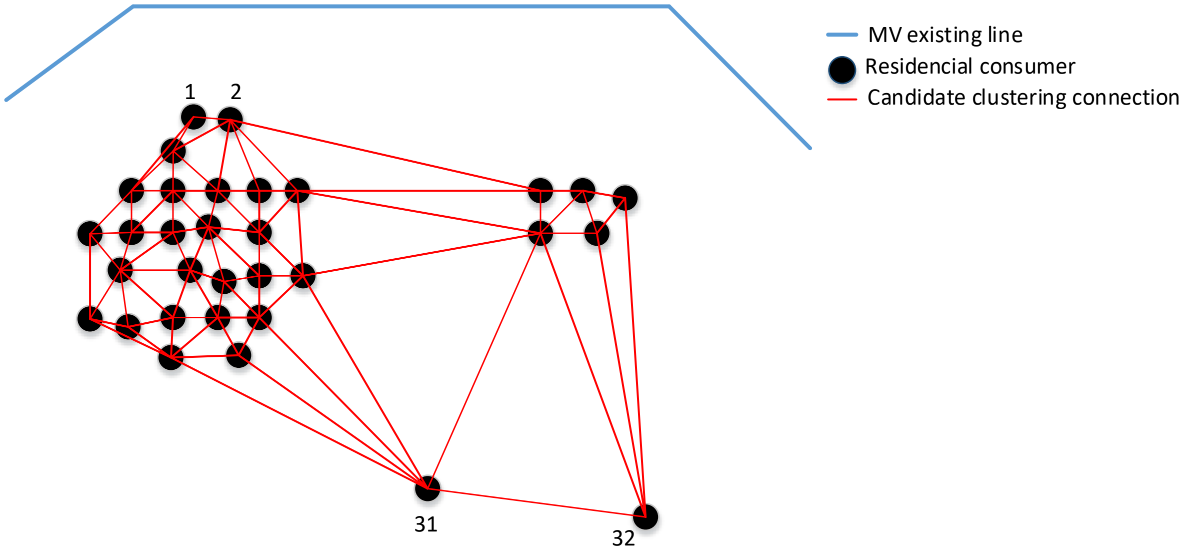

Figure 20: Clustering candidate connections

Figure 20 adds the candidate connections to the example shown in Figure 19. Using the consumer identifiers of Figure 20, it is clear that consumers 1 and 2 could be electrified together, but a direct connection between them and consumers 31 and 32 is not worth considering. However, by following the logic that is explained in the following subsection, consumers 1 and 32 could be electrified together if economies of scale justify the gradual aggregation of more customers until all of them happen to be connected in one large cluster.

3.4.2.1 Off-grid clustering process

The first step of the clustering process (off-grid clustering) temporarily assumes that all the consumers will be electrified individually with off-grid systems. Next, the algorithm makes customer grouping decisions on the basis of two conflicting driving factors: (1) the savings in generation, operation and management costs brought by economies of scale in larger mini-grids, versus (2) the increment of network costs associated to grouping customers together.

REM begins by evaluating the arcs of the Delaunay triangulation that are more likely to be activated by joining the corresponding clusters, i.e., from the shortest to the longest link (the effect of the order of evaluation is mitigated by running several passes). In each evaluation, the model compares the costs of the configurations shown in Figure 21 to determine if the connection should be activated. In the figure, triangles represent generation sites, and the line may represent either a MV or a LV connection (least-cost feasible option).

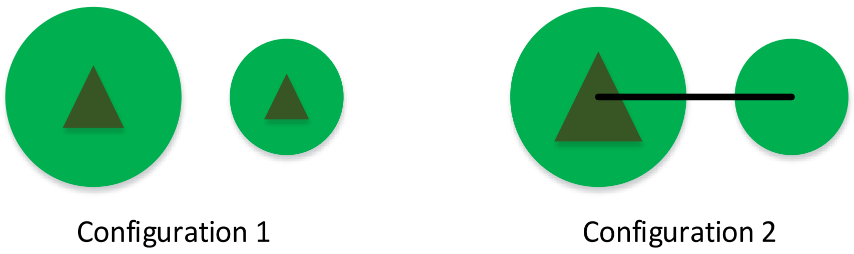

Figure 21: Off-grid clustering configurations

Configuration 1, where the clusters are separately electrified, has larger generation and management costs. On the other hand, the network cost of configuration 2 is larger (the line approximates the incremental network costs). REM estimates the cost difference between both configurations (generation costs are obtained from the look-up table described in previous sections) and joins the clusters if configuration 2 is less expensive. Figure 22 shows a possible off-grid clustering solution with seven off-grid clusters for the example under consideration, and the Delaunay arcs that have not been activated.

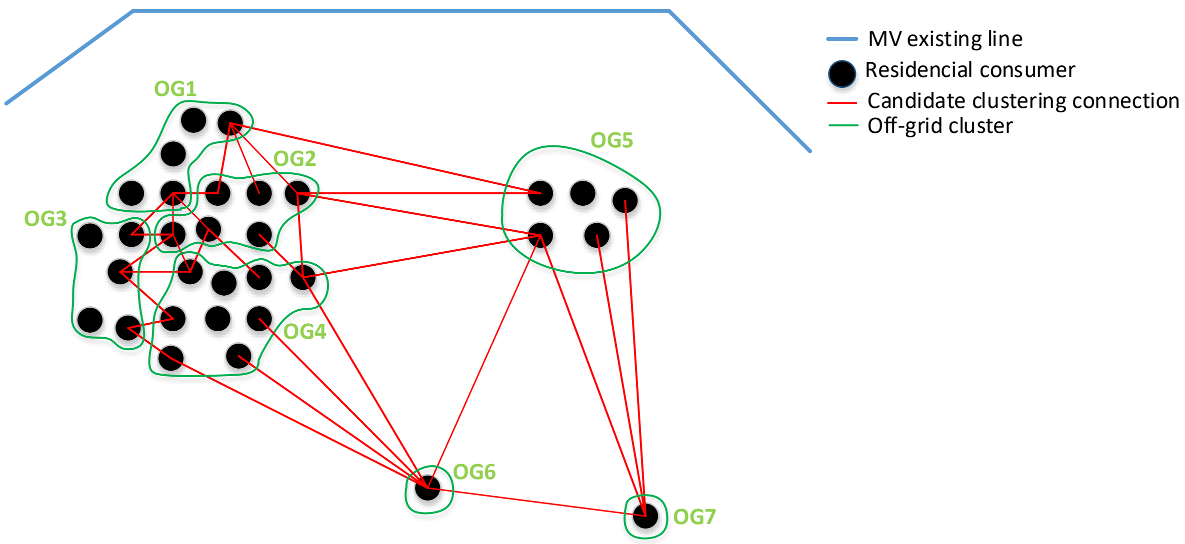

Figure 22: Off-grid clustering example

Delaunay arcs are used as potential clustering connections; therefore, some of them may be redundant (if they link the same pair of clusters) and just ignored. The clusters at the end of this step are the off-grid clusters, and they are the starting point of the grid-extension clustering process.

3.4.2.2 Grid-extension clustering process.

The second step of the clustering process (grid-extension clustering) starts from the existing network and the off-grid clusters obtained in the first clustering step. Note that REM does not decide the final electrification modes in the clustering process. This is determined in the final designs phase, described in the following section, when the different alternatives derived from the clustering process are examined and final detailed comparisons are made.

The grid-extension clustering makes use of the arcs of the Delaunay triangulation that join pairs of two different off-grid clusters. It calculates the cost of several configurations to determine if it is worth to join both clusters, under the assumption that at least one of them is going to be a grid-extension. It is important to note that this assumption may not be true eventually, and it has to be interpreted just as a different clustering criteria).

In the first set of configurations, which is shown in Figure 23, clusters are connected to one another (triangles represent here MV/LV transformers, thick lines represent MV connections, and thin lines LV connections). This implies that REM will join both clusters if a configuration from this set ends up being the least-cost one.

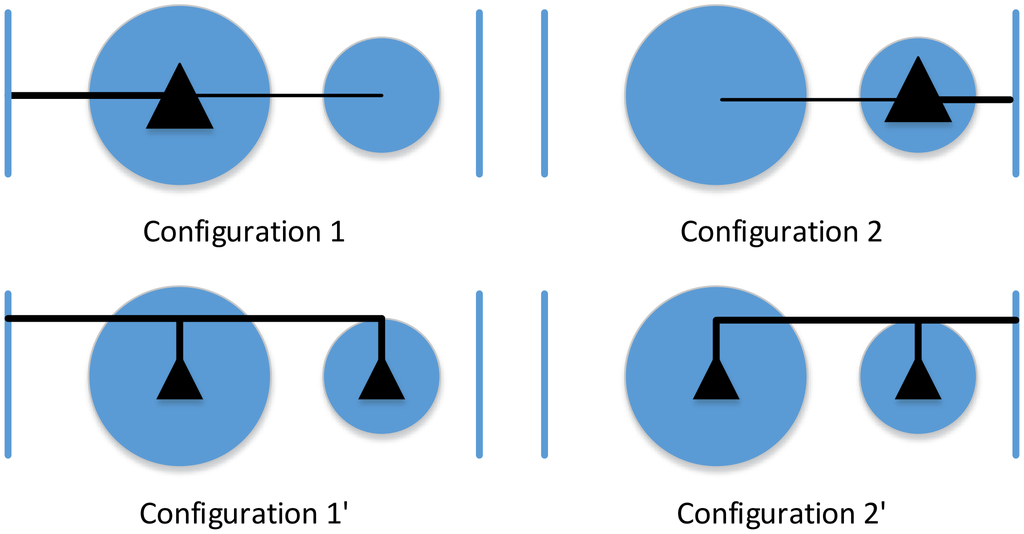

Figure 23: Set of alternative configurations that support merging grid-extension clusters together

On the other hand, Figure 24 shows several configurations with the clusters not connected to one another. In configurations 3 and 4 one of the clusters is indeed electrified with an off-grid system (triangles inside off-grid systems represent generation sites, triangles inside grid extensions represent transformers, and thick lines represent MV connections). Hence, if a configuration from Figure 24 is the least-cost one then REM will not connect both clusters.

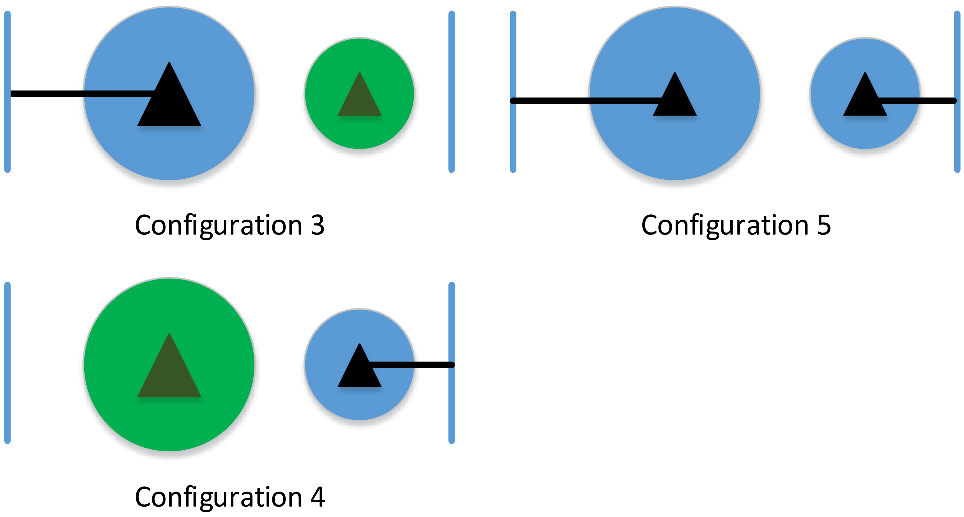

Figure 24: Set of alternative configurations that support keeping grid-extension clusters separate

The clusters at the end of this step are the grid-extension clusters. Following with the example, Figure 25 shows the corresponding clusters at the end of the grid-extension clustering process and the Delaunay arcs that have not been activated.

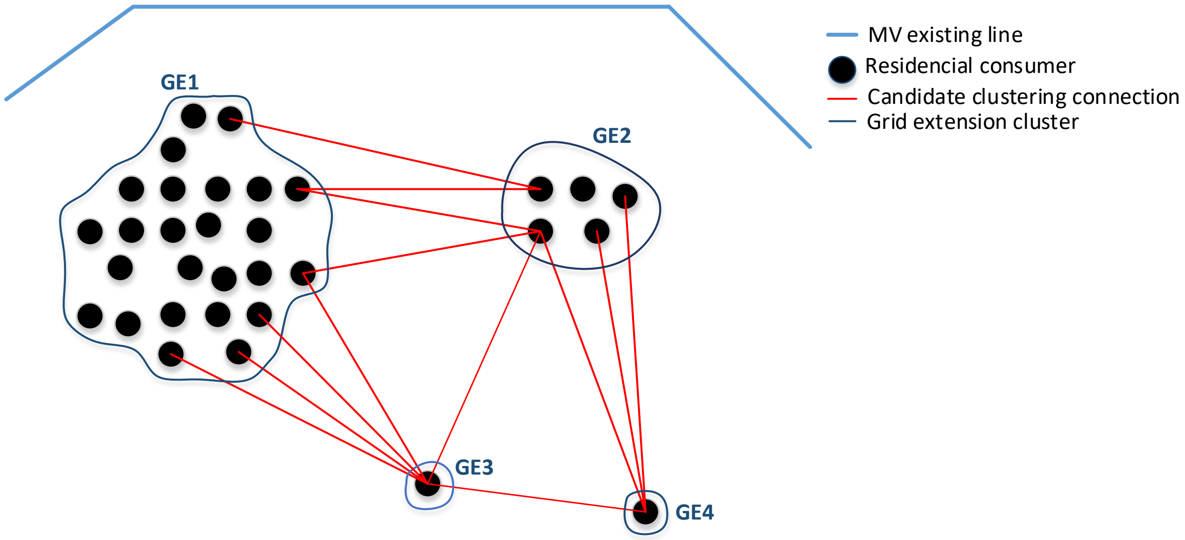

Figure 25: Grid-extension clustering example

The clustering process creates a hierarchical structure of clusters where the first level contains the grid-extension clusters, the second level contains the off-grid clusters and the third level contains the individual consumers. Figure 26 shows the structure that corresponds to the example.

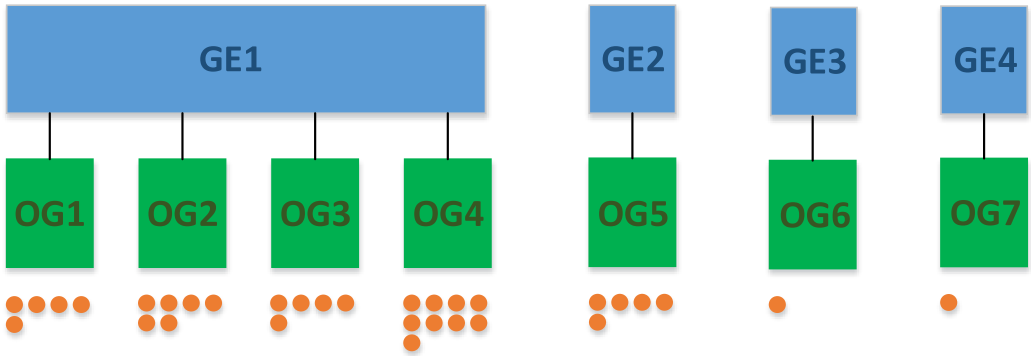

Figure 26: Hierarchical structure of clusters in the example

This cluster structure is used to determine the electrification mode of each consumer and the final solution. However, it is important to note that the origin of each cluster –GE or OG– is completely ignored in the final design phase, and both electrification options (off-grid and grid-extension) are tried and evaluated in detail for all the clusters. The only goal of the clustering processes is to deliver a well-defined, compact, and meaningful structure of clusters to be thoroughly explored in the final design phase.

3.4.2.3 Other approaches

The hierarchical structure of clusters shown in Figure 26 is created using a bottom-up greedy approach, where individual consumers form the initial clusters. However, a different strategy, currently under development (Oladeji, 2018), is to start with a large grid-extension cluster that contains all the consumers, and then proceed with a bottom-up evaluation of disconnections.

The first step of this top-down strategy is to calculate a detailed network design connecting everyone to the network. Then, REM would systematically evaluate the removal of lines and transformers, considering the least cost scenario. Cost reductions in the grid would be compared with the cost of electrifying the corresponding downstream consumers with off-grid systems.

This clustering algorithm would determine which consumers are better electrified with grid extension designs and which are left in off-grid systems. However, it would still be necessary to find the optimal off-grid solution, following the off-grid clustering process described previously or an equivalent strategy.

3.4.3. Final designs

In this process, REM exploits the hierarchical structure of clusters to determine the best electrification mode of each consumer, which belongs to three nested clusters: the individual consumer, its off-grid cluster and its grid-extension cluster. Since the number of candidate systems is significantly lower now, REM can afford to compute off-grid and grid extension solutions for each cluster regardless of its position on the hierarchical structure. This implies that grid extension designs and mini-grid solutions are calculated for all the clusters.

Specifically, REM obtains the least-cost electrification solution for a cluster by comparing its least-cost electrification mode (mini-grid or grid extension) with the sum of the best electrification solutions of the clusters that are in the immediately lower level. Therefore, cost evaluations are propagated bottom-up in the clusters structure.

Although this may seem counterintuitive at first (off-grid clusters where calculated without considering the grid), it is actually better to proceed this way. Isolated consumers may be large factories, so their best electrification solution could be a grid extension even if there are no other consumers close to them.

In the example of Figure 26, let us consider the structure below GE1. First, REM would find the cost of electrifying individually the consumers below OG1. Each one could be provided with an individual generation set or connected to the grid. The best combination of individual solutions is the temporary optimum solution for the OG1 set of consumers, and it is compared with the best electrification solution for OG1 as a single connected system, either off-grid or grid-extension. The least cost solution becomes the temporary optimum solution for the OG1 set of consumers.

The same process is applied to the consumers in OG2, OG3 and OG4, respectively. The resulting group of least cost solutions becomes the temporary optimum solution for the GE1 set of consumers (note that this solution may include a combination of isolated consumers, mini-grid and grid extension systems).

The final step is to compare this temporary optimum solution with the best electrification option for GE1 as a single connected system, either off-grid or grid-extension. The least cost solution becomes the final optimum solution for the GE1 set of consumers.

Figure 27 shows a possible final electrification solution for the example under consideration. In this case, the cluster GE1 is electrified with a grid extension design whereas the remaining grid-extension clusters have lower costs when electrified with off-grid systems that are coherent with the hierarchical structure.

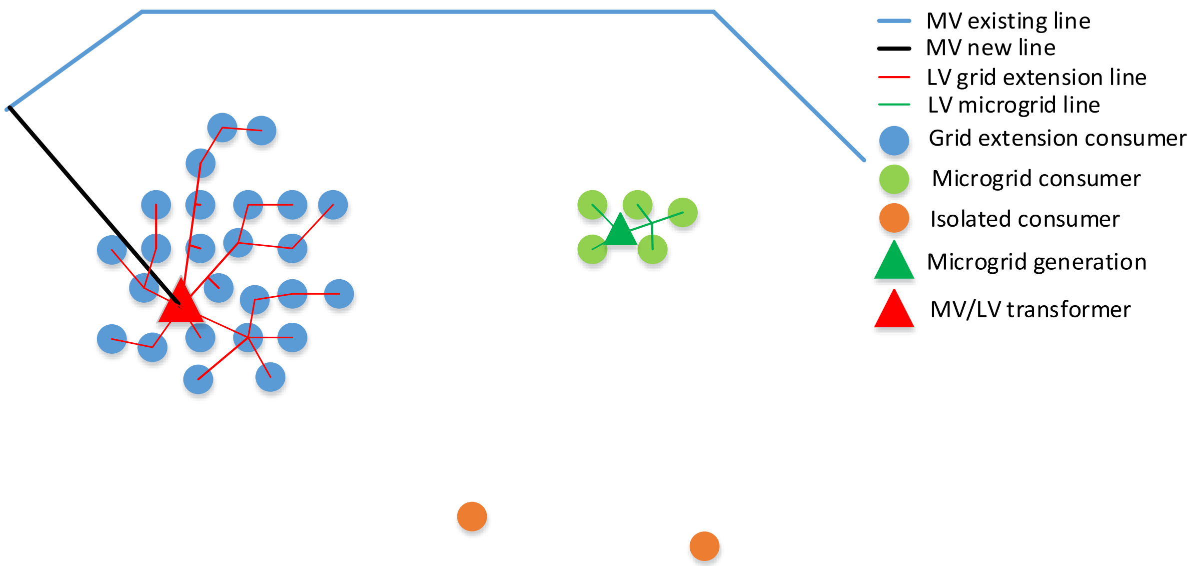

Figure 27: Final electrification solution

In this stage, accurate network designs are calculated for the cost comparisons performed to determine the final electrification mode of each consumer. REM uses RNM (Reference Network model), a software tool described in (Mateo Domingo et al., 2011), to obtain the optimal network layouts and the corresponding costs.

3.4.3.1 RNM as a network designer.

RNM is a flexible tool that is able to design a quasi-optimal distribution network from scratch, calculating the corresponding costs. The model can design the entire distribution network starting from the transmission/HV distribution substations, or only the medium and low-voltage components, or only the low-voltage network.

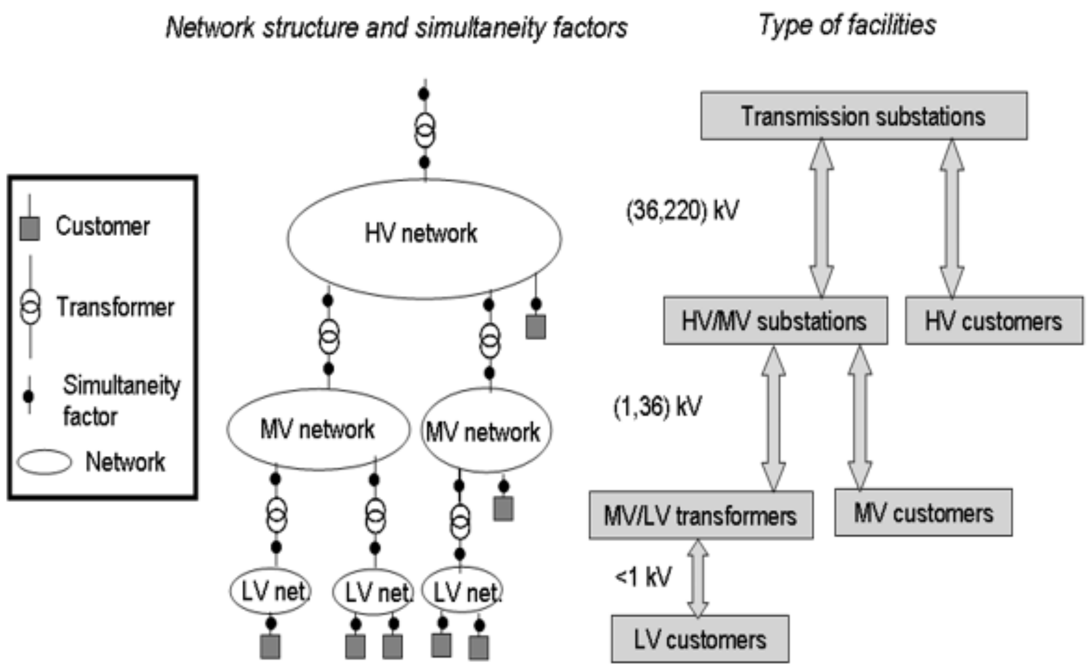

Figure 28: Network structure overview (figure source (Mateo Domingo et al., 2011))

This computer model needs as input the location of the transmission substations and the customers, as well as techno-economic information related to the catalog of components (mainly lines and substations/ transformers). If RNM is used to design only a part of the distribution network, the locations of the corresponding substations are required too. Figure 28 provides an overview of the network structure created by RNM.

RNM minimizes cost, subject to the usual electrical constraints such as maximum allowed voltage drop and maximum capacity. The model selects the best elements among a defined catalog of components, and it considers the influence of topography when calculating a network layout. RNM also allows forbidden and penalized zones (areas that lines should avoid and where substations should not be located). More details about topography in RNM have been provided in section 3.3.3.

3.4.3.2 Network design for mini-grids and grid extensions.

In order to obtain the network design for a mini-grid, REM uses RNM twice with different configuration parameters. REM assumes that all the mini-grids have a low-voltage generation system and evaluates two possible networks:

- LV network. REM assumes that the mini-grid has a low-voltage distribution network. Generation is also at LV, so no transformers are needed.
- MV and LV network. REM assumes that the mini-grid has a MV network, and MV/LV transformers with LV sub-networks to reach the customers. Generation is assumed to be at LV, so an extra MV/LV transformer is needed to feed the MV network.

The final network design for the mini-grid is the least expensive one. As expected, REM selects low-voltage designs for small mini-grids and medium-voltage designs for large ones, where the "size" of a mini-grid here must be understood as a combination of distance, number of consumers, and total load. Figure 29 shows examples of both types of networks, one with only LV and the other one with MV and LV.

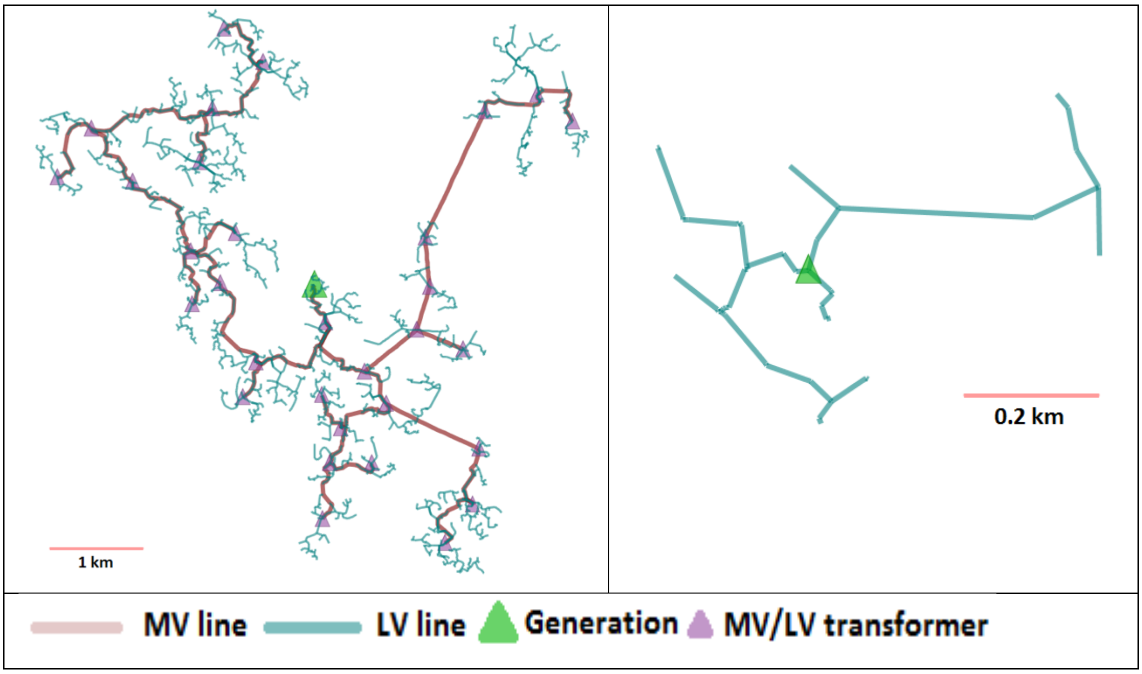

Figure 29: Mini-grid network layouts

Note that REM uses RNM only once when calculating a grid extension design. RNM computes the medium-voltage and low-voltage distribution networks of the corresponding grid extension.

3.4.3.3 Dealing with solar kits.

For low levels of demand, DC solar kits could be preferred to AC generation systems as the electrification solution for small isolated consumers. Although AC stand-alone systems can provide more energy, solar kits are more portable and less expensive, especially when it comes to operation and maintenance costs, and they could suffice for the small demands of many poor households. This implies that solar kits are an option that is worth considering in a rural electrification plan (Sun, 2017).

The cost of non-served energy is critical here, since many solar kits are usually meant to provide less energy at a very low cost, and only for a few hours a day. Therefore, the energy consumption of solar kits users will typically differ widely from their expected demand, since solar kit users will have to adapt their use of electricity to the availability of energy both in terms of peak energy and total available hours of use. This is a particular case of supply limitations. As already mentioned in sections 3.2.2 and 3.3.6.2, REM defines a different value of non-served energy, applicable to solar kits or any other supply limitations, to estimate the social cost of non-served energy due to supply limits.

The solar kits option is not fully compatible with a bottom-up clustering strategy, because they may break the monotonicity of the economy of scale saving that makes clusters grow. Because of this, REM only considers solar kits as an electrification option in the final phase, when deciding the best electrification mode of isolated consumers.

3.5. REM outputs.

In Section 3.1 the standard REM process was presented as made of five sequential blocks, from “Data Preparation” to “Post-processing and Reports”. Each block produces certain results and outputs, either intermediate or final. REM generates text files in different formats, spreadsheets and figures. Some of these files are processed further to generate more elaborated reports, via scripts and tailored applications.

Some output tables and figures will be shown in the large case example in Section 4. In this section 3.5, the different types of outputs are related to the specific REM building blocks, adding comments about the interest of each output. Outputs are in general optional, especially those intended for debugging and troubleshooting.

3.5.1 Data preparation.

REM inputs are complex, and in some cases they are generated by partially automated tools. This is the case of demand models, including building locations and demand profiles. Some intermediate outputs are useful as feedback to the user, to prevent input errors and to check data consistency:

- The list of buildings can be checked out in spreadsheet format, in a XY-referenced figure (see Figure 32), and in a geo-referenced GIS figure.

- The segments that define the MV existing network can be inspected as well in spreadsheet, XY (see Figure 32) and GIS formats.
- Demand profiles and patterns can be analyzed in tabular format and graphical representations (see figures 11 and 31).
- Polygons of penalized zones and altitude raster maps can be visualized in XY and GIS figures (see Figure 12).

3.5.2 Mini-grid generation design.

This block is of paramount importance for the electrification plan, and it contains complex simulations, optimization algorithms and cost-balance procedures that have to be thoroughly checked. The design process generates both intermediate and final results, some of which are useful to understand and monitor the results supplied by REM:

- Hourly generation dispatch, both in spreadsheet and graphical formats (see Figure 34).
- The evolution of the optimization process leading to the calculation of each generation design point is logged in a spreadsheet format. It is only used for debugging and input-analysis purposes.
- The final look-up table with the optimal designs for the representative mini-grid configurations, both in spreadsheet format (see Table 3) and in a graphical format (only for a limited number of consumer types, as in Figure 33).

3.5.3 Clustering.

Clusters are critical intermediate artifacts in the electrification planning process, and they respond to the REM fundamental search of the optimal balance between generation savings (economies of scale) and network investments. All the outputs from this block are meant for debugging and input-data analysis purposes.

- Delaunay triangulation, displaying the neighborhood relationships considered in the clustering processes (in XY graphical format).
- Log of clustering decisions, both in off-grid and grid-extension clustering processes (spreadsheet format).
- Off-grid and grid-extension clusters, both in spreadsheet and XY graphical format (see figures 38 and 39).
- Clustering statistics, in spreadsheet format, describing the distribution of clustering sizes in terms of number of consumers.

3.5.4 Final designs.

REM explores the structure of clusters and calls RNM (for precise network designs and costs) in order to determine the optimal combination of stand-alone systems, mini-grids and grid extensions. Therefore, some outputs from this block are directly generated by RNM to describe in detail the network of each final subsystem, while other outputs are generated by REM making partial use of RNM results.

The main outputs generated by RNM for each subsystem (mini-grid or grid extension) are:

- Network lines costs, in HTML files, for MV and LV networks.
- Network transformers costs, in HTML files, for MV/LV elements.
- Distribution network total costs analysis, in HTML files, for MV and LV networks.
- Losses, reliability and quality analysis, in HTML files, for MV and LV networks.
- Detailed list of components, in HTML files, for MV and LV networks. They include the list of transformers, lines, posts and other elements such as breakers, capacitors, voltage regulators, and even maintenance brigades.
- Detailed network layout in several shapefiles (different types of elements are represented in separate files). This allows representation of final results as in Figure 41.

The main outputs generated by REM are:

- Results by customer. In a spreadsheet format, each entry on the table corresponds to an individual customer with its electrification mode.
- Results per system. In a spreadsheet format, each entry on the table corresponds to an independent system (either mini-grid or grid extension), although standalone systems of the same type are grouped in a single row). Design, cost and quality parameters are described in detail.
- Results summary. Overall results for each type of electrification mode, in a spreadsheet format. A reduced version of this output is shown in Table 4.

3.5.5 Post-processing and reports.

Using the outputs from the final design block, and some relevant inputs, REM and other ancillary tools generate reports, figures and tables. Figures are in Matlab formats, Shapefiles and KML files (see figures 41 and 42). GIS files store multiple attributes of the electrical objects represented, which is useful for an interactive analysis of the solutions. Especially meaningful is the global representation of all the subsystems in a single electrification map (see Figure 41) showing the penetration and location of grid extensions, mini-grids and standalone systems under different color codes.

4. Application to a large case example.

This section describes the application of REM to a realistic case that can be assumed to be representative of a rural area in many sub-Saharan African countries. All the data, including the layout of the existing network, the location of buildings, the catalog of components and the demand profiles have been obtained from actual studies in some of these countries.

4.1 Case Description

The considered region has an area of about 65 x 40 km and 52,709 unelectrified consumers, most of them rural but some of them peri-urban. This region contains 17 different customer types (see Table 2), including several residential customers (types 1 and 2), community customers (types 3 to 10) and productive customers (types 11 to 17). Their respective energy demands have been estimated considering the consumption of similar loads in other rural areas already electrified (natural demand). The data information was provided by African utilities, considering also the results from the field study in the Rwandan village of Karambi, Gicumbi district developed by the UEA Lab and detailed in (Santos-Pérez, 2015; Li. 2016).

Customer type	Description	Peak load year 10 (kW)	Energy year 10 (MWh/yr)
1	Lower-income household	0.08	0.26
2	Higher-income household	0.40	1.31
3	Community hall	1.60	5.26
4	Local government office	1.12	3.28
5	Health center	1.44	4.73
6	Small health center	0.80	2.63
7	Nursery school	0.32	1.05
8	Primary school	0.32	1.05
9	Secondary school	1.04	3.42
10	Technical school	20.80	68.33
11	Telecommunications tower	224.00	735.84
12	Large irrigation pumping	240.00	788.40
13	Small water pumping	32.00	105.12
14	Small agroindustry	1.20	3.94
15	Large agroindustry	304.00	998.64
16	Small mining facility	20.00	65.70
17	Village market	6.40	21.02

Table 2: Classification of customers, with peak power and energy consumption

Figure 30 shows a sample of hourly profiles obtained from the Karambi field study, which have been used to compute the hourly demand curve for a whole year considered for this case. It resembles the average use of appliances reported by the different customer types in the canvased village in week and weekend days, also considering seasonality.

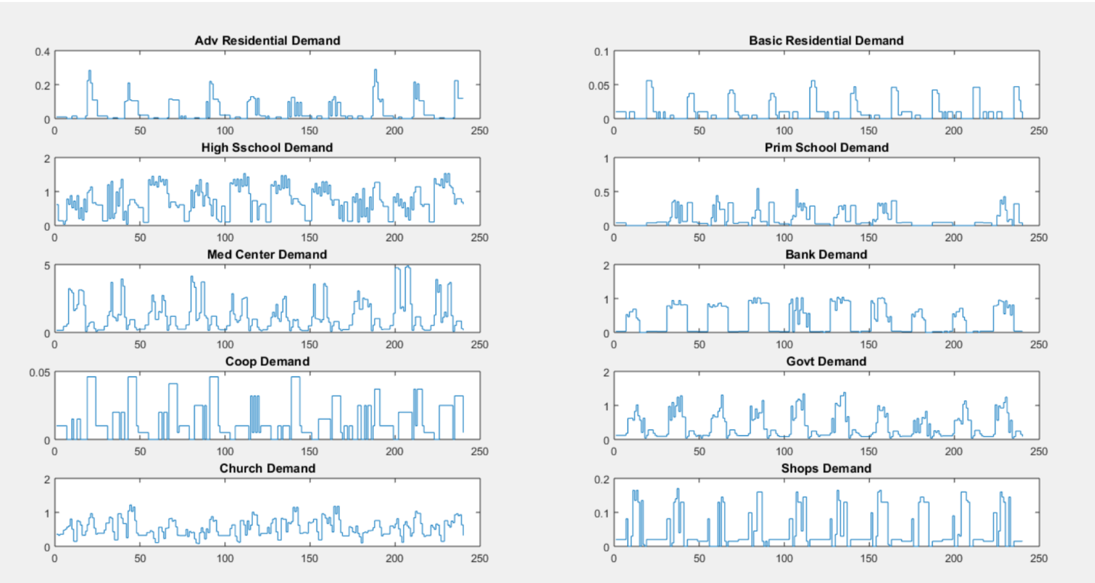

Figure 30. Sample demand profiles for domestic, community and productive loads in Karambi village (Li, 2016)

Figure 31 shows the resulting profiles of the daily critical and non-critical demands. There is a 0.30 $/kWh penalty for not meeting the non-critical demand, and 0.75 $/kWh penalty for failing to meet the critical one. In other words, these are the costs of unserved energy for these two demand profiles.

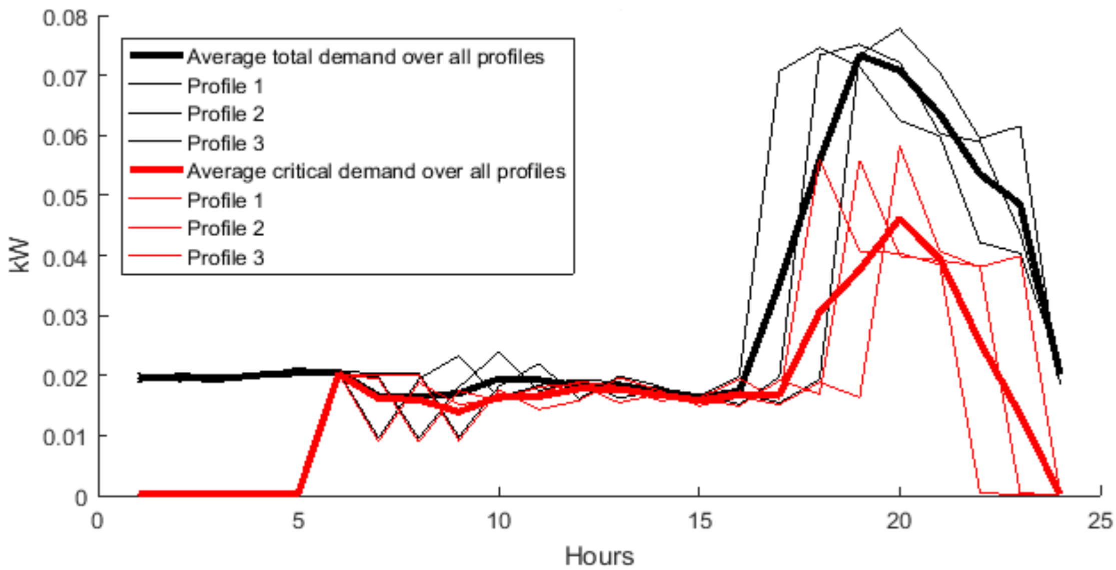

Figure 31: Demand profile samples at the final year of demand growth

The main grid is assumed to be available at any time with a probability of 90% and the wholesale energy cost at MV distribution level is 0.1 $/kWh at any connection point. Although REM allows hourly specification of reliability, and diversity of reliability and energy cost among feeders, in this case such possibility has not been used.

The mini-grid generation design allows combinations of PV, batteries and a diesel generator, used as a backup and required – in this case example – to supply no more than 30% of the total demand.

The objective is to design the optimal electrification plan for the demand that is expected to be reached in 10 years from the present time. This demand, represented in Figure 31, results from applying a constant growth rate of 2 % per year to the estimated present demand over the 10 years' time period (22% of accumulated growth).

The economic life for the main distribution network components is set to 40 years, whereas for mini-grid network components a lifespan of 20 years is considered. The lifespans of batteries, PV panels and other components are defined in the corresponding catalogs. The financial discount rate for grid extensions and mini-grids is 10% per year, and 15% for isolated systems.

The individual connection costs are $65 per consumer for both mini-grids and grid extensions. The management annual cost is $9 per consumer for grid extensions and very large mini-grids, and $16 per consumer for medium size mini-grids of about 150 consumers (values estimated from mini-grid operators in East Africa). REM has been set not to accept mini-grids with five consumers or less. In the clustering algorithm, the annual management cost for individual low-demand households with solar panel and battery has been set to $60[4]. In the final stage of REM, once the clusters have been obtained, standalone systems for lower-income households (customer type 1) are turned into solar kits for the final electrification plan.

Note that the comparison between solar kits and the other two delivery modes is not straightforward. The choice of solar kits over the other two delivery modes cannot be determined solely on the basis of the single parameter of the cost of non-served energy. It can be very expensive to achieve with solar kits reliability levels that are comparable to those that can be more economically obtained with mini-grids or a reliable grid connection. However, solar kits with what many households might consider an acceptable reliability level exist at modest prices and with attractive financing schemes. Solar kits are individually managed without any external interference and the availability of power can be focused on the individual household priorities, but they can only supply low electricity intensity appliances and no community or productive loads. In this example the solar kit available in the component catalog, with an investment cost of $86.4, can meet 68% of the given household demand. A conventional solar home system using the same mini-grid technology would meet 95% of the demand with an investment and operation cost of 181 $/yr, as shown in Table 3 (CAPEX + OPEX).

The generation and network catalogs have been built by blending data gathered by members of the MIT/Comillas Universal Energy Access Lab team from several studies conducted in sub-Saharan African countries and India. Topographical data (altitude raster map and forbidden zones) are from (DIVA-GIS, 2018).

[4] Source: Communication from Peru Microenergía (www.accioname.org), a social enterprise that provides supply to almost 4,000 individual households in isolated areas in the Andean Cajamarca.

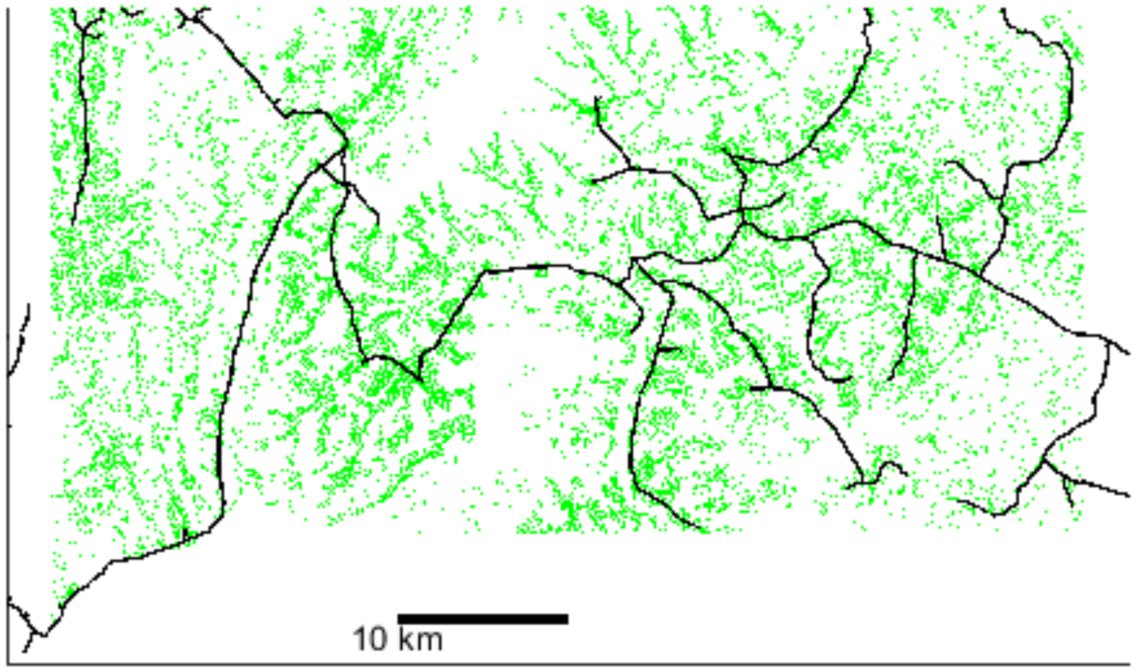

Figure 32: Unelectrified consumers (green dots) and MV power grid (black lines)

Figure 32 shows the location of the 52,709 unelectrified consumers and the existing MV distribution power grid.

4.2. Mini-grid generation design

REM creates a look-up table calculating generation designs for 1, 10, 50, 100, 250, 500, 5,000 and 50,000 sample demand profiles, which are chosen sequentially from the ones shown in Figure 31. As mentioned in sections 3.1 and 3.2.2, when REM needs to estimate the cost of a candidate mini-grid with a different number of aggregated demand profiles, it will interpolate between the two closest designs unless the number of aggregated demand profiles is larger than 50,000. For larger numbers, REM assumes that there are no more economies of scale in generation, so the per-unit investment and operation costs are the same as in the generation design for 50,000 aggregated demand profiles.

Table 3 shows the characteristics of the designs for the look-up table samples. Note that the management costs (part of the OPEX shown in Table 3) are calculated assuming that each sample profile corresponds to a low-demand residential consumer. Internally, REM uses the actual number of consumers of a cluster to compute management costs, not the number of sample profiles (since a type of consumer may comprise multiple sample profiles).

Generation designs meet almost all the demand, which is reasonable given the penalties for non-served energy. Diesel generators are part of the generation designs provided for the 5,000 and 50,000 points of the look-up table. In both cases, they cover 26% of the total demand, which is below the maximum allowed (30%). The constraint on diesel utilization is active, since the optimum unconstrained value has 74% of diesel production (as shown in section 6.1). This case does not reach exactly the 30% limit because (1) the discrete sizes of diesel generators, and (2) the hourly logic of the load-following dispatch is not able to meet medium-term targets accurately.

Number of Sample Profiles	1	10	50	100	250	500	5,000	50,000
Peak Demand (kW)	0.08	0.78	3.86	7.71	19.28	38.55	385.50	3,854.98
Average Demand (kW)	0.03	0.30	1.50	2.99	7.47	14.95	149.48	1,494.79
Solar Capacity (kW)	0.25	2.25	11.50	23.25	57.75	115.50	834.00	8,286.00
Battery Capacity (kWh)	1.38	17.94	85.56	169.74	425.04	861.12	5,382.00	53,820.00
Generator Capacity (kW)	0	0	0	0	0	0	125	1,250
Fraction of Demand Served	0.95	0.99	0.99	0.99	0.99	0.99	0.98	0.98
Percentage of Diesel Used (p.u.)	0	0	0	0	0	0	0.26	0.26
CAPEX per Demand Served ($/kWh)	0.29	0.22	0.21	0.20	0.20	0.20	0.14	0.14
OPEX per Demand Served ($/kWh)	0.44	0.23	0.13	0.09	0.06	0.06	0.10	0.10
Non-Served Energy Cost per Demand Served ($/kWh)	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Cost per Demand Served ($/kWh)	0.76	0.45	0.34	0.30	0.27	0.26	0.25	0.25
CAPEX ($/yr)	71	570	2,652	5,225	12,998	26,130	183,476	1,829,165
OPEX ($/yr)	110	584	1,627	2,319	4,170	7,257	128,333	1,237,319
Non-Served Energy Cost ($/yr)	9	14	103	200	528	868	8,176	84,725
Total Cost ($/yr)	189	1,168	4,382	7,744	17,696	34,255	319,985	3,151,210
CAPEX per Profile ($/yr)	70.75	56.99	53.05	52.25	51.99	52.26	36.70	36.58
OPEX per Profile ($/yr)	109.54	58.35	32.53	23.19	16.68	14.51	25.67	24.75
Non-Served Energy Cost per Profile ($/yr)	8.67	1.44	2.06	2.00	2.11	1.74	1.64	1.69
Total Cost per Profile ($/yr)	188.95	116.79	87.64	77.44	70.78	68.51	64.00	63.02

Table 3: Generation design samples in the look-up table

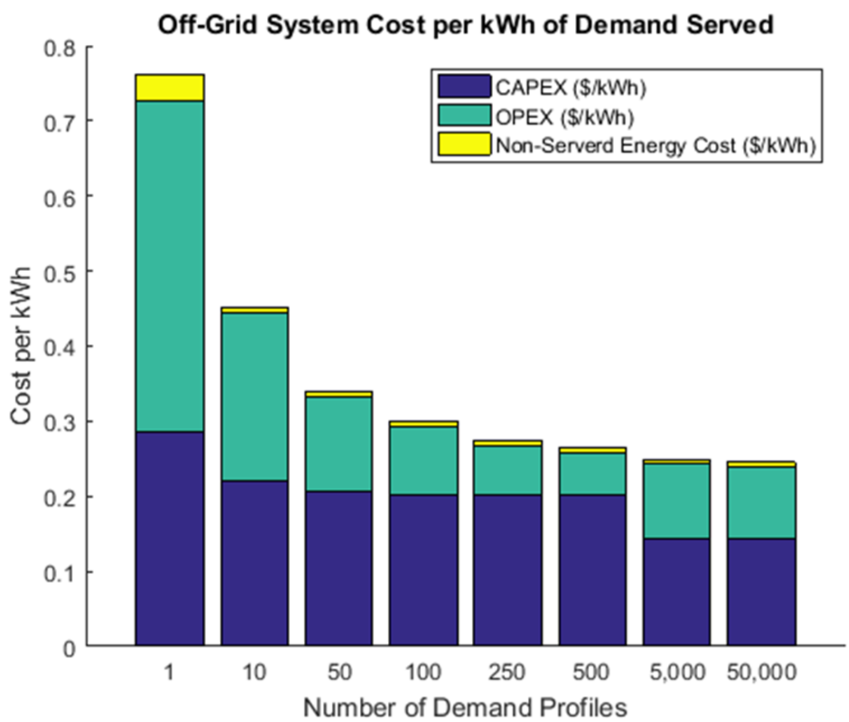

Figure 33. Off-grid system cost per kWh of demand served

Figure 33 shows the costs of generation (CAPEX and OPEX) plus non-served energy for off-grid systems (network costs will be calculated later for each candidate mini-grid).

REM provides the hourly generation dispatch of each mini-grid and standalone system. The detailed simulation that REM performs over one year (with some optional simplifications to reduce the computational burden) allows the user to analyze days with different patterns of demand coverage, as in Figures 34 and 35.

Figure 34 shows the dispatch for a couple of days in a mini-grid with 10 demand profiles. Solar panels serve the demand and charge the batteries during the day. At night, batteries meet most of the demand.

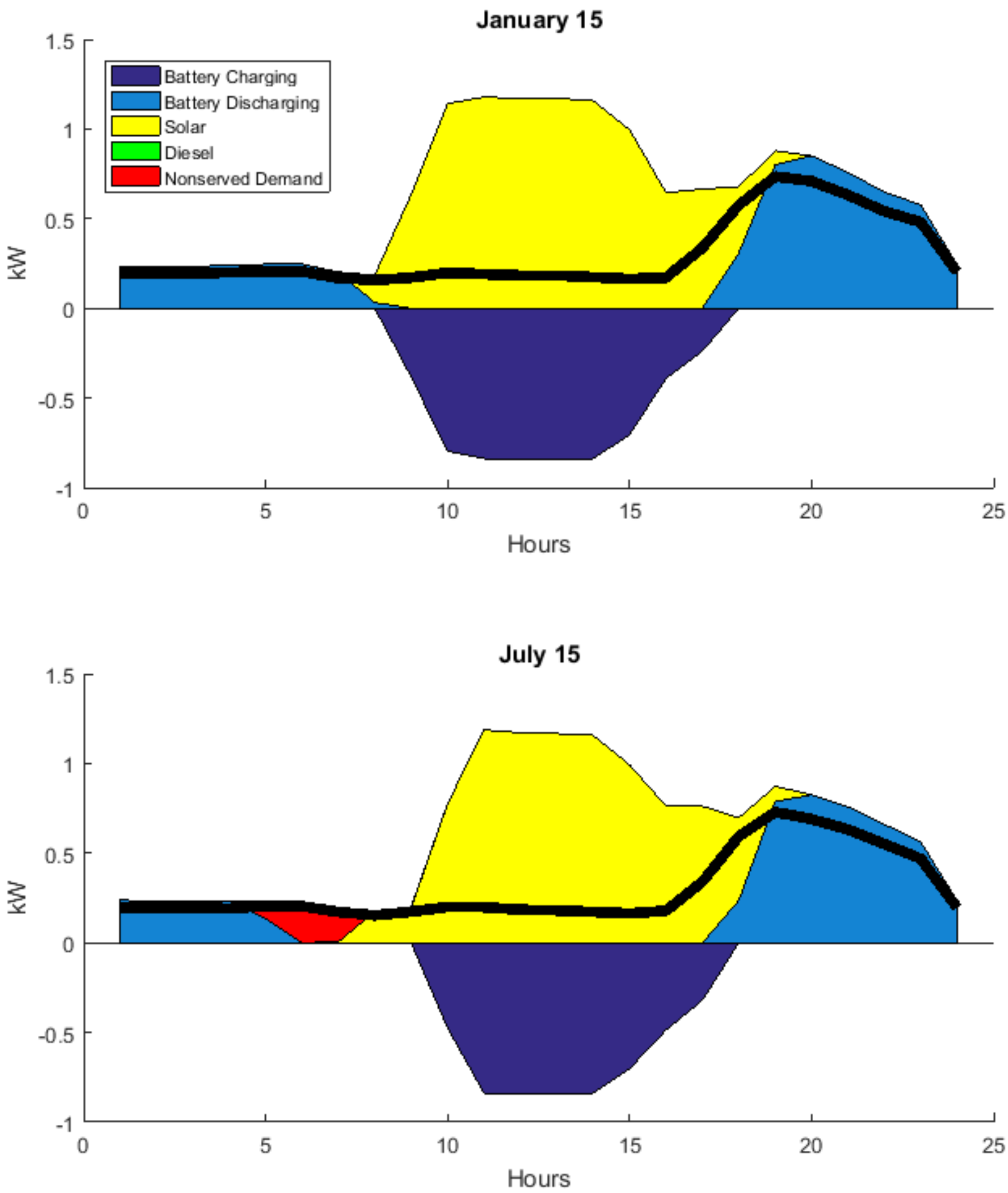

Figure 34: Daily sample dispatch of a mini-grid with 10 demand profiles, where the black line represents the total demand (critical plus non-critical)

Figure 35 shows the dispatch for a couple of days in a mini-grid with 5,000 demand profiles. This generation design also meets the demand and charges the battery with solar panels during the day, but now the demand at night is mostly covered with diesel.

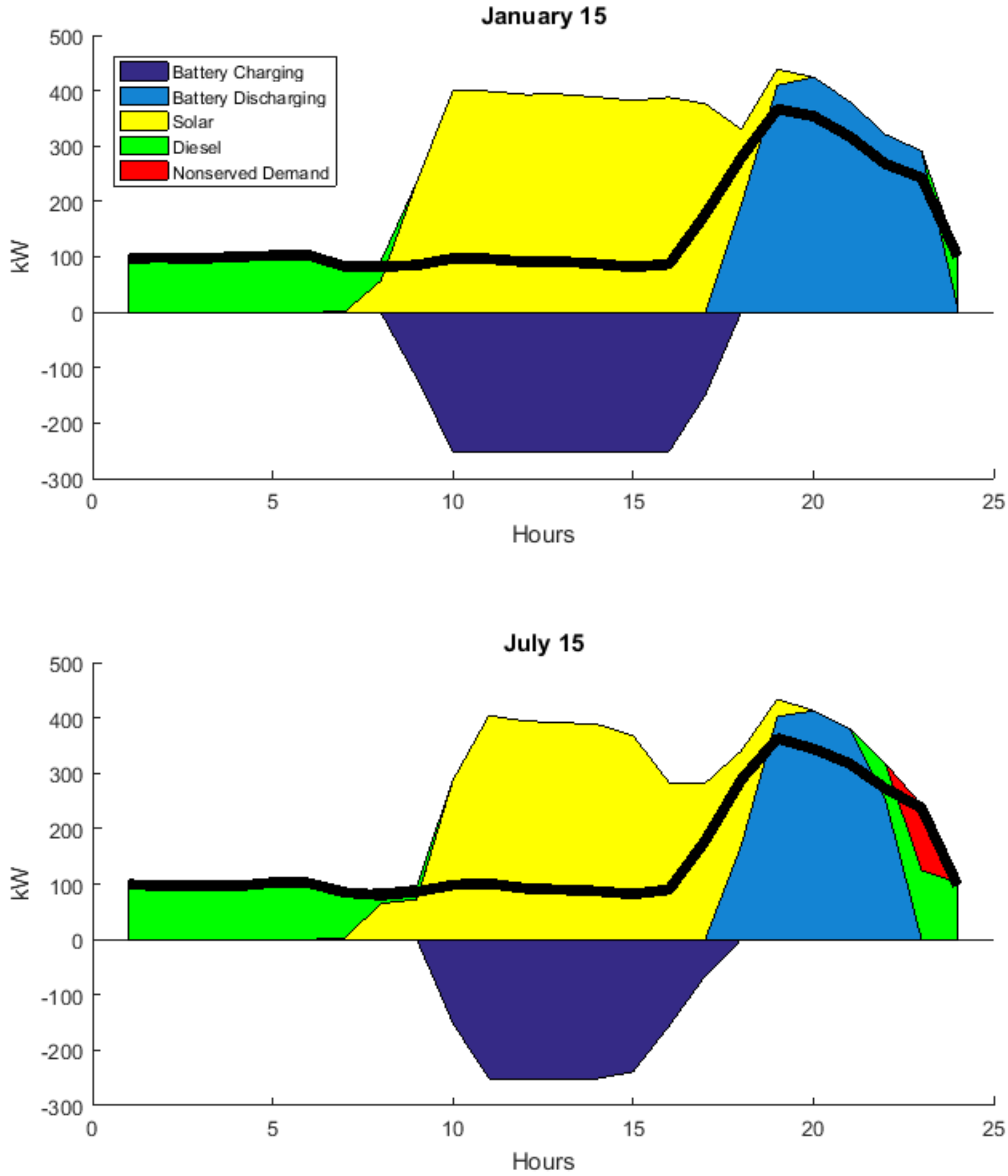

Figure 35: Daily sample dispatch of a mini-grid with 5,000 demand profiles, where the black line represents the total demand (critical plus non-critical)

In addition, the model calculates the amount of demand served for each hour of the day. Figure 36 shows this information for cases provided in Figures 34 and 35

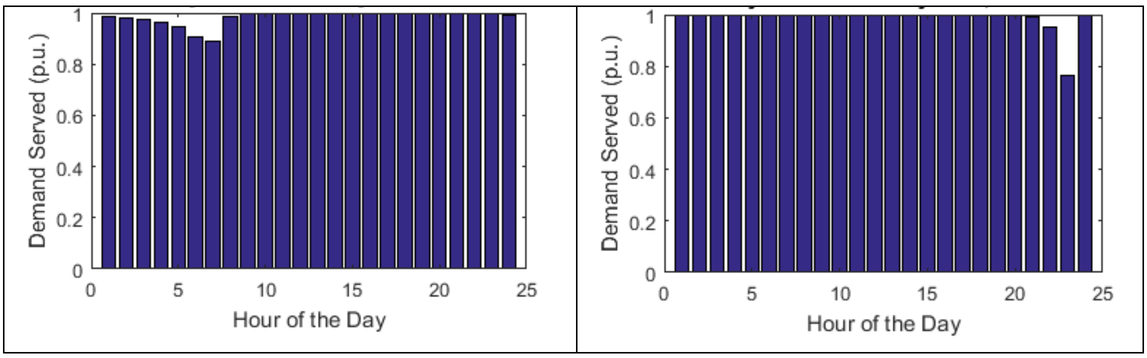

Figure 36: Demand served each hour of the day for 10 (left) and 5,000 (right) demand profiles

4.3. Clustering

The clustering process starts by computing the Delaunay triangulation of the unelectrified consumers. The vertices of the triangulation will be considered as potential connections among neighbor clusters. Figure 37 shows the Delaunay triangulation of this case.

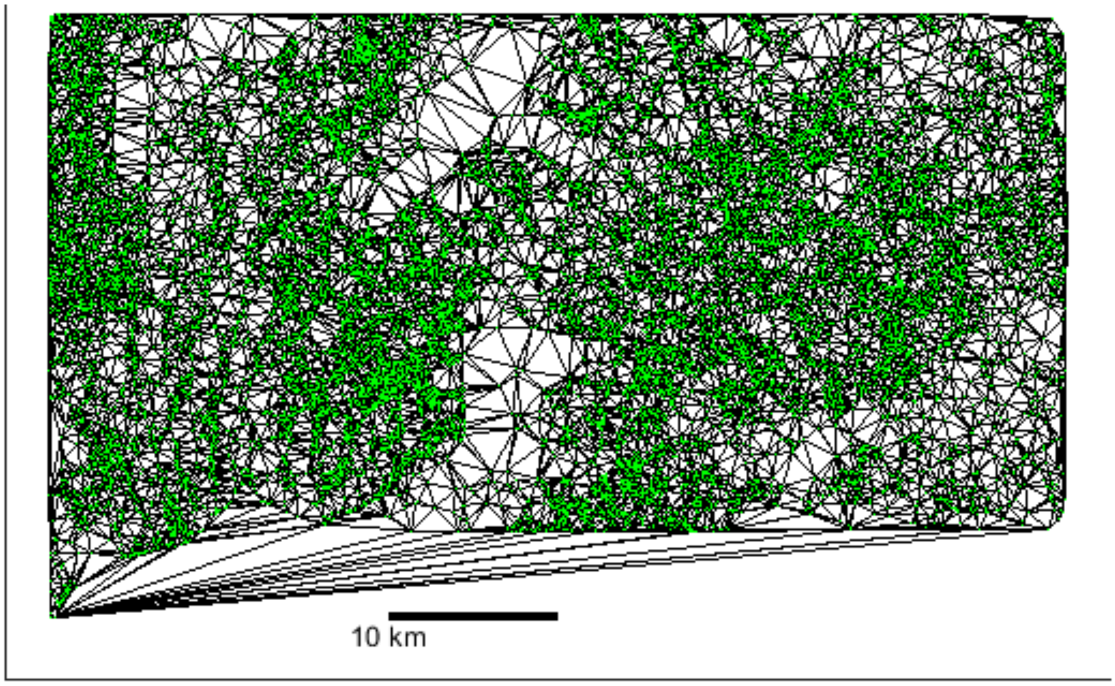

Figure 37: Unelectrified consumers (green) and the corresponding Delaunay triangulation (black)

REM groups the unelectrified consumers into strictly off-grid clusters, by weighing the savings on generation and management costs versus the incremental network cost as clusters grow. Figure 38 shows the off-grid and clusters for the selected region (colors of the clusters are randomly assigned).

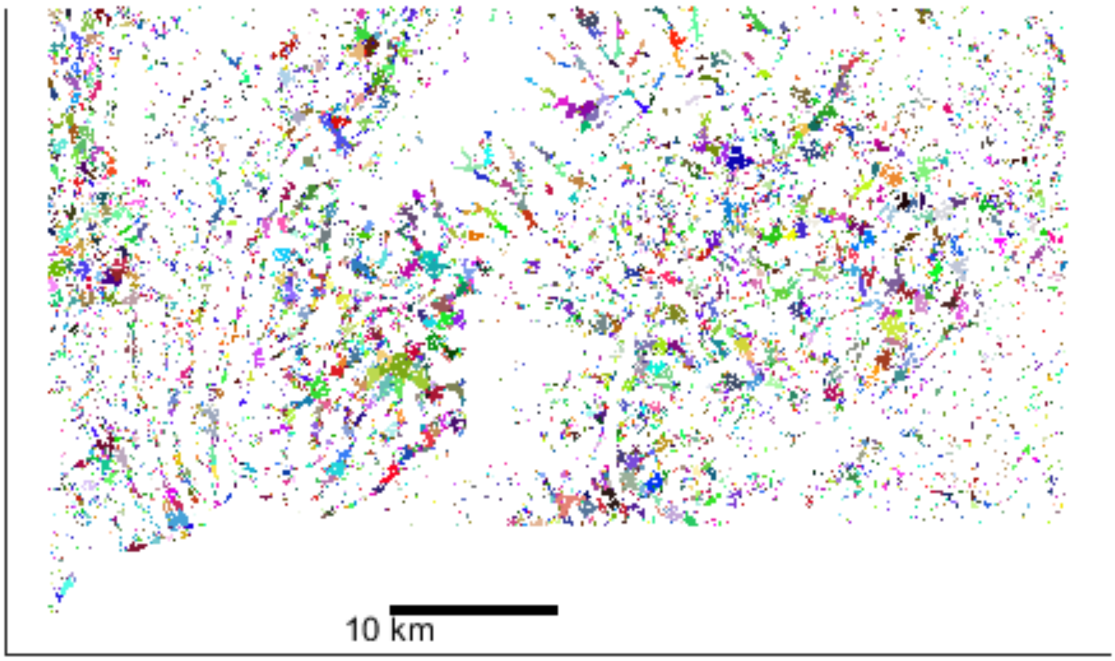

Figure 38: Off-grid clusters

Afterwards, REM tries to aggregate these off-grid clusters and considers grid extension as an electrification option. Since the grid usually has lower energy costs than mini-grids, this may result in bigger grid extension clusters. Figure 39 shows the grid-extension clusters for the case example (colors of the clusters are randomly assigned)

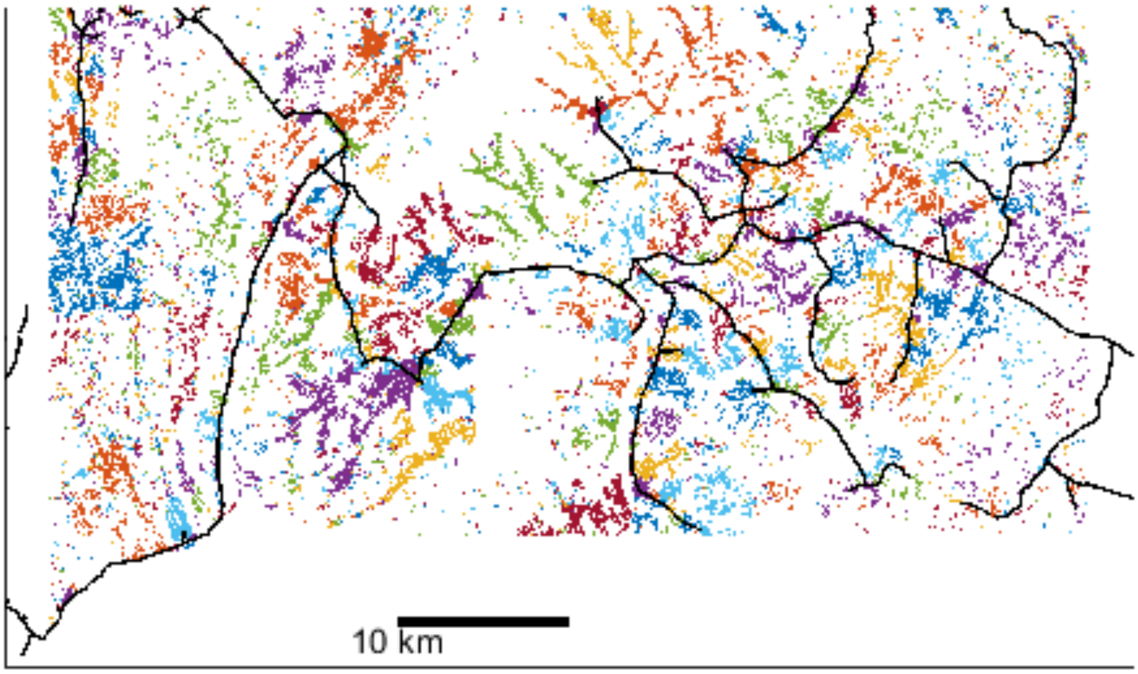

Figure 39: Grid extension clusters and MV power grid (black lines)

Note that, in contrast to other electrification planning methods that are rule-based, REM may find off-grid electrification solutions for consumers that are close to the network, if the off-grid solution is less expensive. This typically happens when the aggregated demand of these customers is so low that – under a cost minimization logic – it does not justify the investment in the minimum size transformer in the catalog and the corresponding wiring cost.

Figure 40 shows the number of consumers per cluster size at the end of the two clustering phases. In off-grid clusters, approximately 70% of consumers are in groups of at most 100 consumers, the reason being that the economies of scale in generation shown in Figure 33 are weaker beyond this point, typically not enough to overcome the extra network cost required for connection.

Grid extension clusters are significantly larger than off-grid clusters. This is to be expected, since the lower cost of energy from the main grid compensates for higher costs of connection. Figure 40 shows that grid extension clusters are about five times bigger than off-grid clusters.

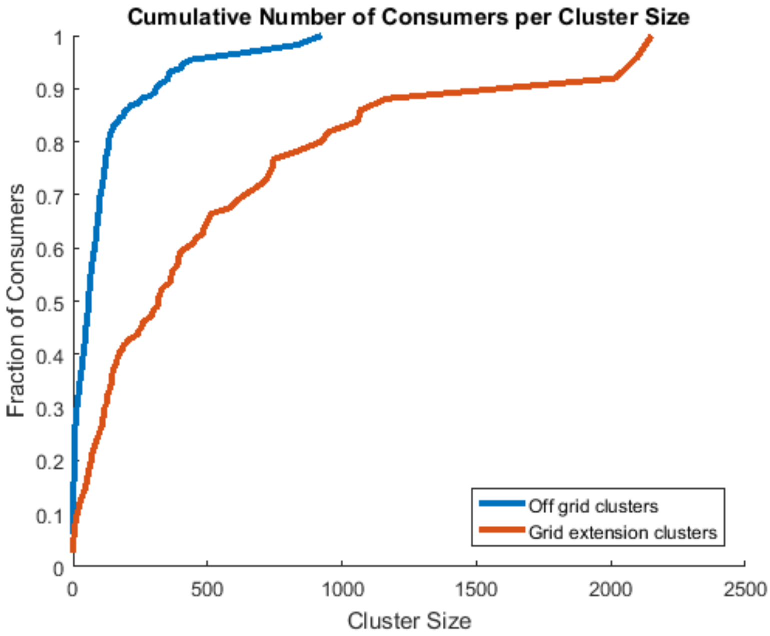

Figure 40: Cumulative number of consumers per cluster size

4.4. Electrification solution

Figure 41 shows the final electrification solution of the case study.

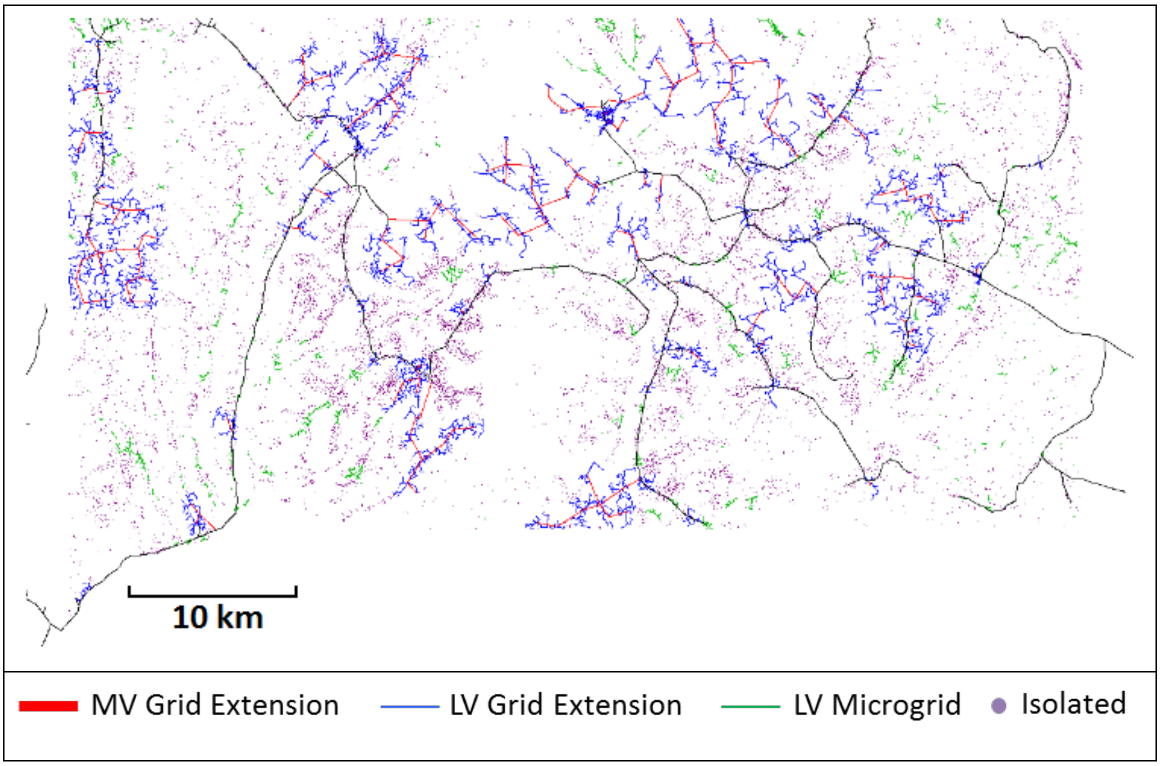

Figure 41: Case study electrification solution. The MV existing power grid is represented with black lines.

REM can project the final electrification solution to Google Earth. Figure 42 shows a grid extension design and the surrounding area.

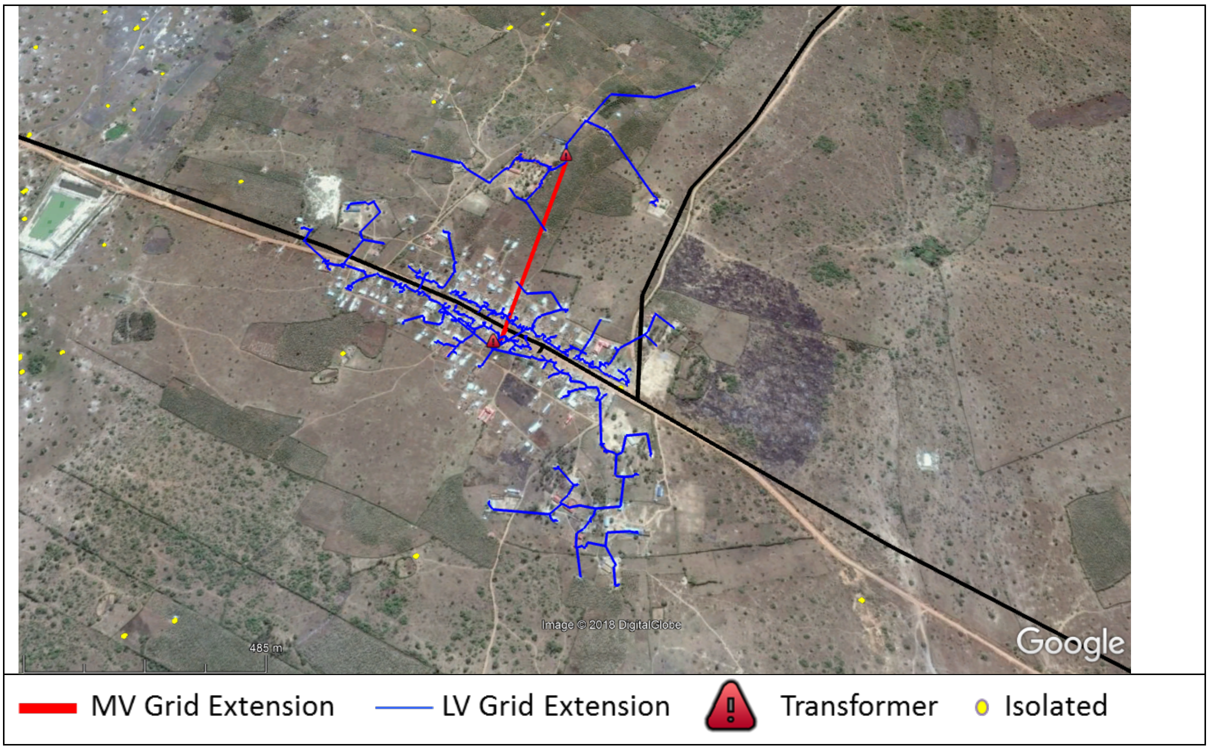

Figure 42: Projection onto Google Earth. The MV existing power grid is represented with black lines.

Table 4 provides a summary of the final electrification solution, where isolated systems are electrified with a combination of solar kits for the residential low-demand households and AC systems for the remaining loads.

	Mini-grids	Isolated	Grid Extensions	All
Number of Customers	8,903	17,148	26,658	52,709
Fraction of Customers	0.17	0.33	0.51	1.00
CAPEX Per Customer ($/yr)	191.69	173.38	94.23	136.44
OPEX Per Customer ($/yr)	49.83	49.50	141.73	96.20
Non-served Energy Cost Per Customer ($/yr)	5.28	53.99	66.90	52.29
Final Cost Per Customer ($/yr)	246.80	276.87	302.87	284.94
Total CAPEX ($/yr)	1,706,576	2,973,177	2,512,065	7,191,818
Total OPEX ($/yr)	443,677	848,847	3,778,261	5,070,785
Total Non-served Energy Cost ($/yr)	47,041	925,818	1,783,549	2,756,408
Final Cost ($/yr)	2,197,293	4,747,841	8,073,876	15,019,011
Fraction of Demand Served (p.u.)	0.986	0.903	0.900	0.911
Cost Per kWh of Demand Served ($/kWh)	0.312	0.313	0.206	0.245

Table 4: Case study electrification: solution summary

The "Final Cost" row is calculated by adding the total investment and operation cost, and the non-served energy cost. Total investment (CAPEX) and operation (OPEX) costs include:

a) Network costs, which are computed with RNM
b) Connection costs, on a per-customer basis
c) Generation costs, which are
    - Generation investment and operation cost in off-grid systems

- “Wholesale energy costs”, which include also transmission and HV network costs, in grid extensions

d) Management costs (mentioned in sections 3.2.5 and 3.3.6.1)

Note that the average final cost per consumer provided in Table 3 is higher for grid extensions, which could lead to the wrong conclusion that it would be better to replace some of them with off-grid solutions. However, REM chooses the best electrification option for each cluster, so any change would result in a worse techno-economic solution. In this case, the higher cost per consumer in grid extensions is due to the presence of several customer types with different demands. Since larger demand loads are typically in grid extensions, their cost per consumer is higher, but the cost per kWh is lower, as expected.

Figure 43 shows the total system cost per kWh of demand served for grid extensions and mini-grids. This cost is calculated by adding the non-served energy costs to the investment and operation costs. Non-served energy cost per kWh is constant for grid extensions because the grid reliability is uniform, and it is very low for mini-grids due to the penalties for critical and non-critical CNSE.

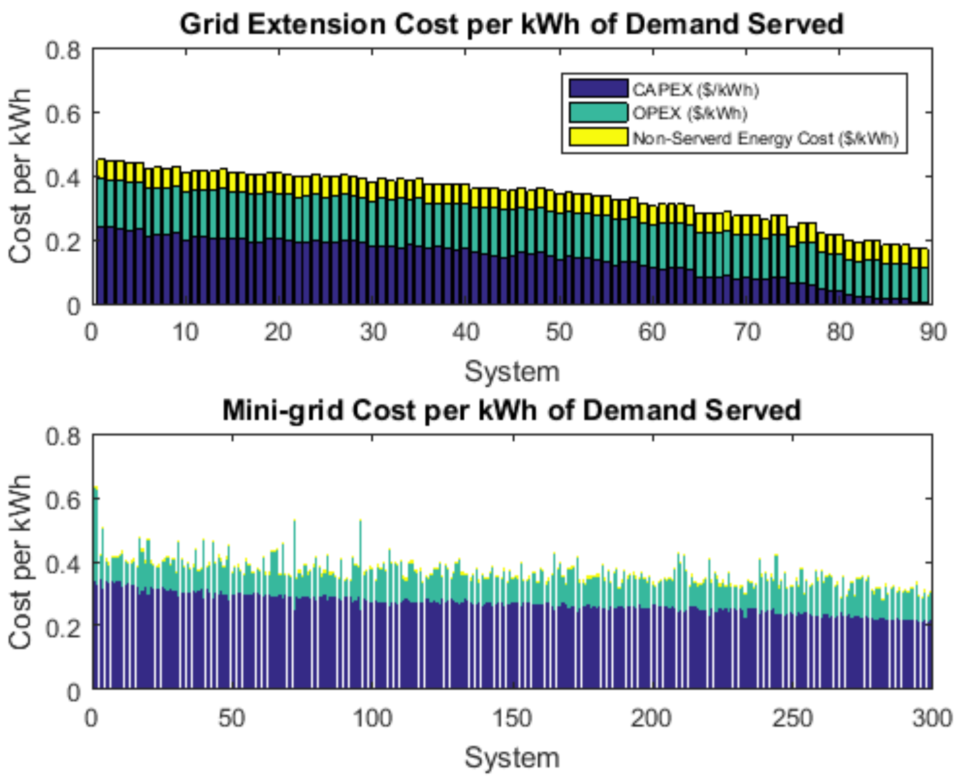

Figure 43: Total costs per demand served in different systems: investment, operation and non-served energy

Figure 44 presents a different cost breakdown for grid extensions and mini-grids, to show the relative weight of generation, network and connection costs for different types and sizes of systems (management costs and CNSE are not represented here). The individual connection costs are an input, and in this example they are the same for all grid extensions and mini-grids (although REM allows different values for each). The energy cost for grid extensions is also an input, and it has been assumed to be uniform all over the grid. Network costs dominate in grid extensions and they show a large diversity due to the dispersion of consumers (this is mainly a rural environment). Generation accounts for the main part of investment and operation costs in mini-grids.

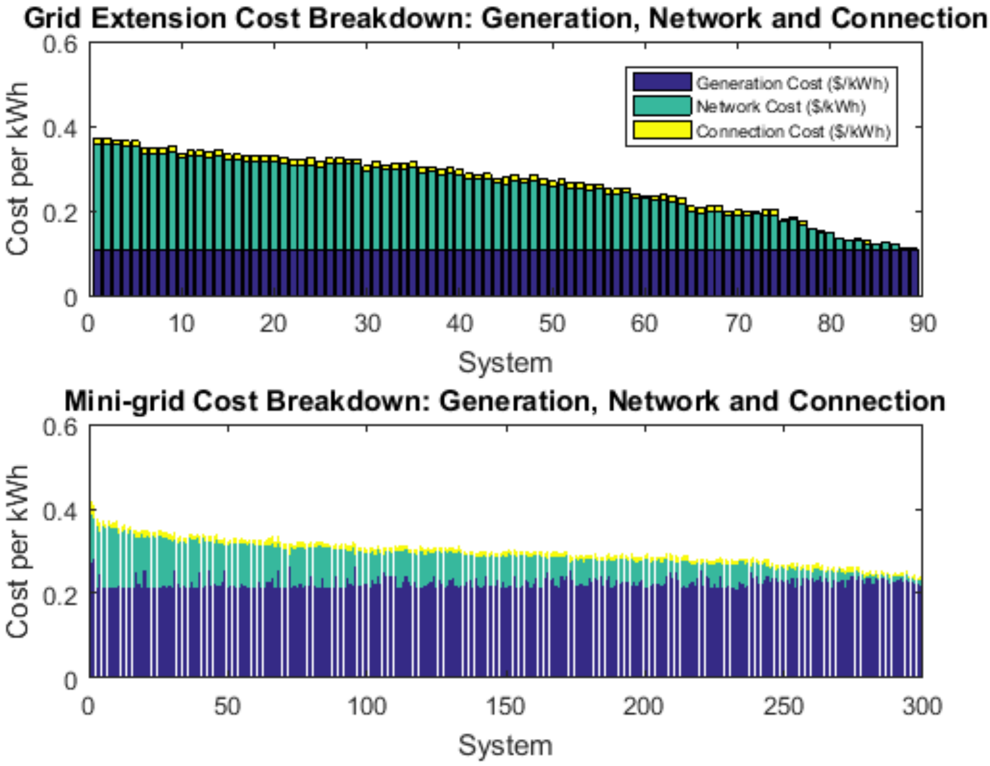

Figure 44: System cost per kWh of demand served: generation, network and connection

Figure 45 shows the total system cost per kWh of demand served for isolated systems. Lower-income households (customer type 1) have solar kits and the remaining loads have AC systems whose data comes from the look-up table. In the case of solar kits, "CAPEX" really represents the total cost of acquisition of the kit, which includes any support service that comes with it.

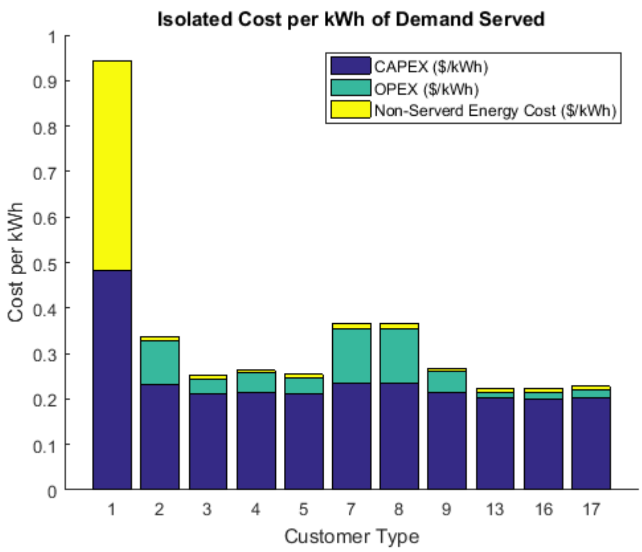

Figure 45: Cost per kWh of demand served of isolated systems.

5. Application to the design of individual mini-grids.

REM includes extensive mini-grid design capabilities which are also relevant for the design and planning of a single mini-grid project. This section describes the alternative use of the REM model which focuses on the design of a single mini-grid at local level, and therefore does not use all the features of REM (no look-up table, clustering or final design phase are needed).

Given a fixed cluster of customers and the associated demand characteristics, REM utilizes the generation optimization algorithm to find the least-cost mini-grid design. This mini-grid design provides electricity service to each customer given the user specified constraints such as reliability level and renewable energy thresholds. The final designs are heavily influenced by generation asset cost, distribution network cost, geographic characteristics of the cluster, and customer demand patterns.

The case study below is an ensemble of non-electrified customers to be electrified through connection to a mini-grid. This case study highlights the mini-grid design and optimization capabilities of REM.

5.1 Case Description and Least Cost Design

A detailed mini-grid design for a representative village in Northern Nigeria shows the capabilities of REM when applied to a single mini-grid design. The Nigerian village is a combination of industrial, commercial, and residential customers. Table 5 below describes the characteristics of each customer type. Each small household consumes electricity for lighting, phone charging, and powering small appliances such as televisions and fans.

Customer Type	Number of Customers	Peak Demand (kW)	Annual kWh	Villiage Peak Demand (kW)	Village Annual kWh
Small Household	764	0.09	275	67.92	209,901
School	1	1.83	4,439	1.83	4,439
Health Center	1	4.87	15,949	4.87	15,949
Religious Center	1	0.91	996	0.91	996
Grinder	1	9.00	36,573	9.00	36,573
Petty Trader	12	0.07	475	0.86	5,699
Phone Service	1	0.50	1,304	0.50	1,304
Restaurant	1	0.55	3,431	0.55	3,431
Tailor	1	0.10	241	0.10	241
Total	783	N/A	63,684	N/A	278,534

Table 5. Description of customer types in the Nigerian Village case study

Figure 46 illustrates the geographic layout of the village. The village is approximately 1 km in diameter and contains a number of smaller clusters located on the outer fringes of the village. The larger village loads such as the grinder, school, and health center are dispersed throughout the middle fringes of the village. The center of the village is almost entirely residential, with a small pocket of traders in the marketplace.

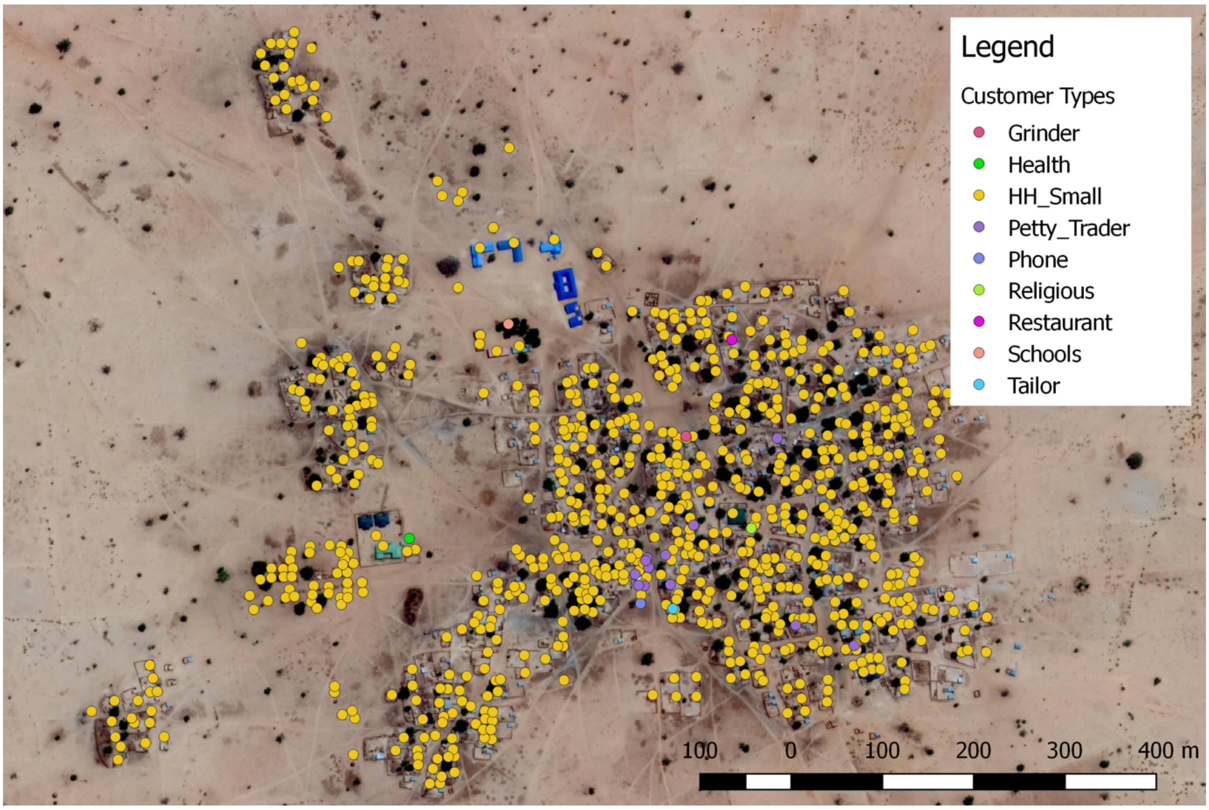

Figure 46. Nigerian Village geographic customer layout. (Note that the blue roofs are an artifact of the satellite imagery, and do not correspond to any particular building type)

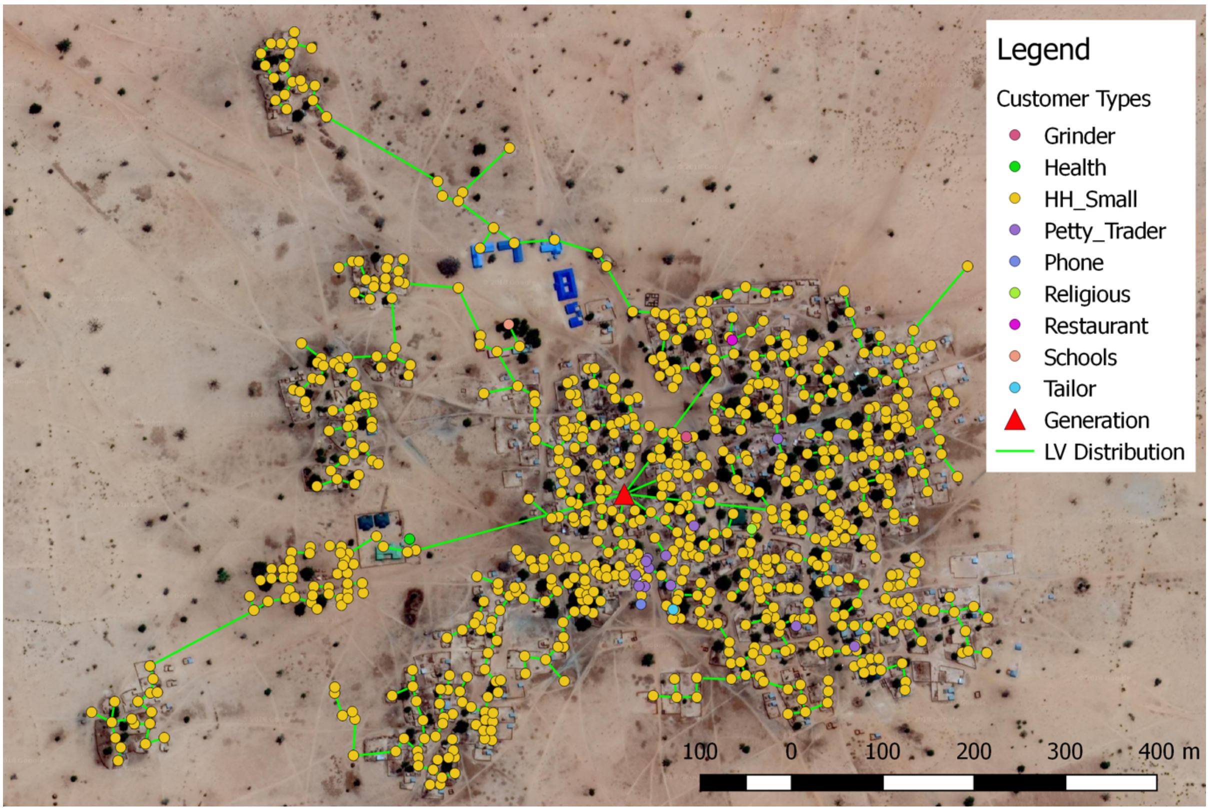

Figure 47. Network design for the Nigerian Village case study

5.1.1 Least-Cost Mini-grid Network Design

Given the existing customer locations and demand patterns, REM produces a least-cost design for the local mini-grid. Absent a specified location for the generation, REM will place the generation assets (Solar PV, Batteries, ICE) at the demand-weighted center of the village. This location typically results in the least-cost network design, but this design may not be feasible due to the location of households, roads, or other existing infrastructure. Figure 47 illustrates the first pass design, which places the generation site at the center of the village and designs the distribution lines to radiate outward. The generation site may require relocation during actual implementation, which will produce slight changes in network design and cost.

In the cases where a generation site is specified and information is available on the roads, streets, or paths along which the poles can be placed, LREM designs the low voltage networks accordingly. An example of this detailed design is shown in Figure 48 below. This type of design is often necessary due to limitation of the placement of generation, existing homes, fields, or other areas which cannot be corridors for the distribution network.

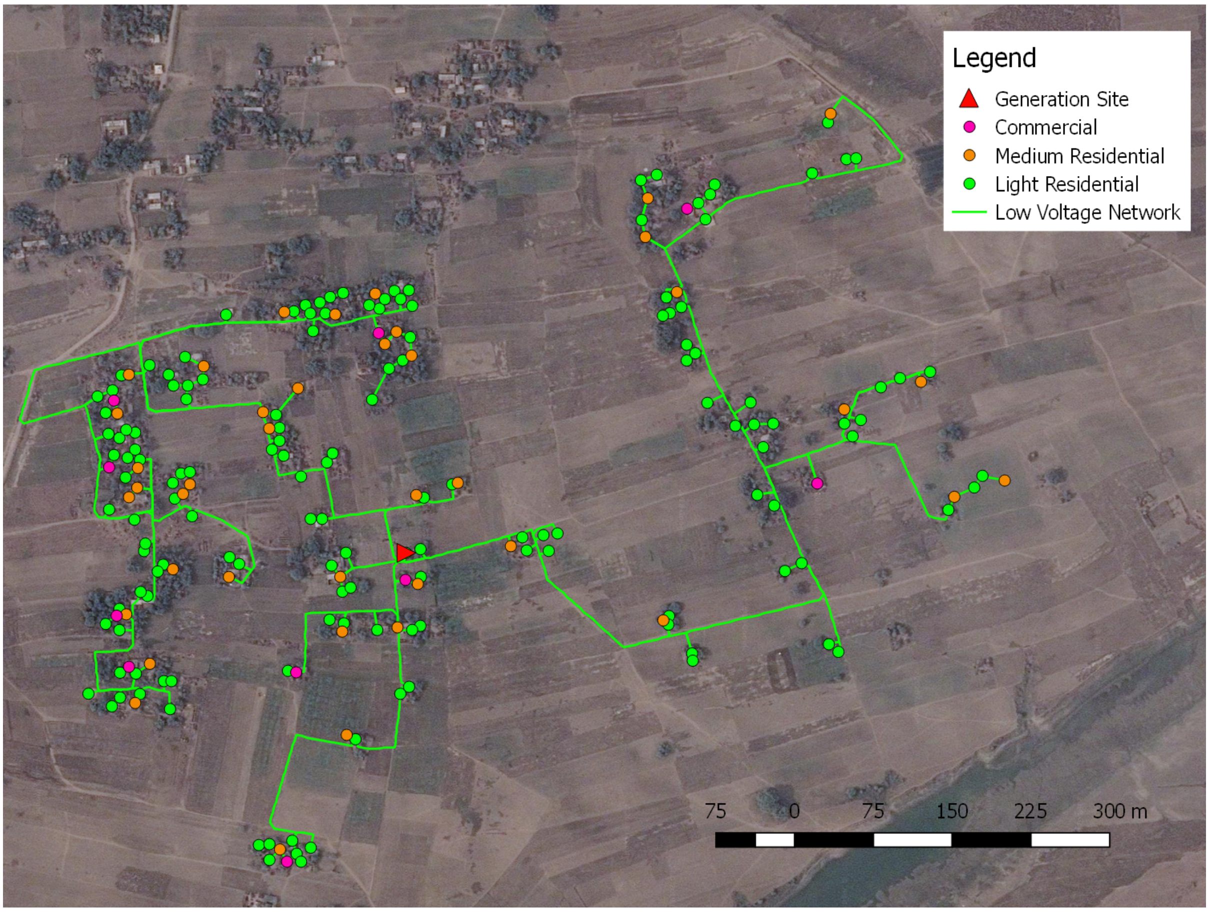

Figure 48. Network design in which the generation site and streets are designated

5.1.2 Least-Cost Mini-grid Generation Design

Figure 49 contains a sample period from the generation dispatch for the Nigerian mini-grid described in Figure 46. This mini-grid design is constrained by a minimum renewable energy fraction of 60%, and has adopted a load-following dispatch strategy. These constraints produce a least-cost design that incorporates solar PV generation, battery storage, and diesel generation. As shown in Figure 49, the diesel generator (ICE) begins providing power once the batteries are depleted to the minimum state of charge. The detailed design specifications for the mini-grid are enumerated in Table 6.

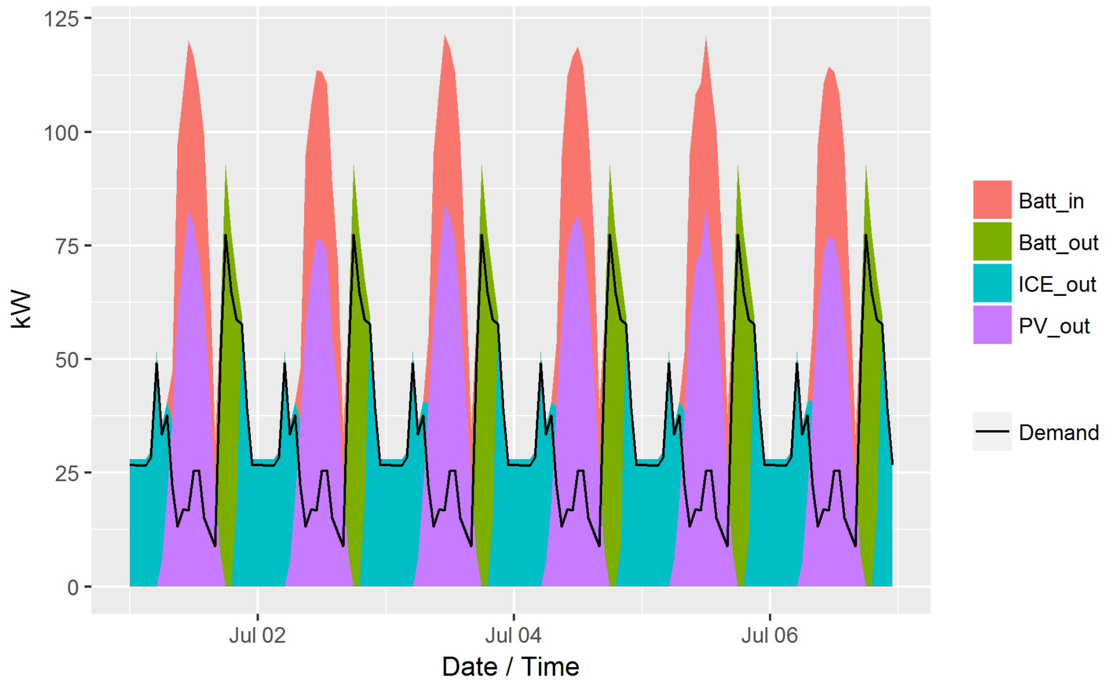

Figure 49. Mini-grid generation dispatch for the Nigerian Village case study

Table __. Nigerian Village Mini-grid Design Characteristics

PV Size (kW)		167
Storage Size (kWh)		845
ICE Size (kW)		60
Inverter Capcity (kW)		81
Charge Controller Capacity (kW)		112
Network Length (km)		12
Investment Cost ($1000 USD)	$	546.91
Annual Fuel Cost ($1000 USD)	$	35.36
Reliability %		100%
Renewable %		61%
Peak Demand (kW)		77
Annual Energy Consumed (kWh)		278,498
Annual Non-served Energy (kWh)		36

Table 6. Nigerian Village Mini-grid Design Characteristics

5.2. Financial analysis.

The detailed technical design provided by REM allows the planner to supplement the design process with a financial analysis of the revenue sources (customer tariffs, potential subsidies, and any other financial arrangements) necessary for an economically sustainable mini-grid project. This financial analysis is expected to yield insights on the impact of discount rates, ownership structures, tariffs, connection priorities, cross subsidization strategies, government subsidies, and concessional loans/grants.

In the example that follows, the Nigerian mini-grid design described above is modeled as a stand-alone project using a project finance framework with an assumed economic life of 25 years. Table 7 shows two potential revenue structures for the mini-grid.

A detailed pro-forma income statement is created to perform the valuation of the mini-grid project. The economically sustainable mini-grid project is assumed to have a Net Present Value (NPV) of zero or above. This strong assumption relies on the proper incorporation of project risk, which is captured in both expected future cash flows and the correct discount rate. In this specific example, a weighted average cost of capital (WACC) is applied to all future cash flows in order to compute the NPV. Additional description of the pro-forma income statement precedes Table 8 below (the income statement).

5.2.1 Revenue Structure: Break-even Tariff

The first (Break-even Tariff) structure is simple. This structure consists of computing and applying to all customers, regardless of their nature or consumption level, a flat volumetric tariff (i.e. $/kWh over the economic lifetime of the project) which results in a project Net Present Value (NPV) of zero. Note that the NPV includes the regulated cost of remuneration of the invested capital. In this example, the weighted average cost of capital (WACC) is assumed as 14.63%. The calculated value of the flat tariff is $0.52/kWh.

5.2.2 Revenue Structure: Tariff with Government Subsidy

The second structure also applies a flat and purely volumetric tariff to all customers, but at a lower rate of $0.40/kWh. An additional government residential subsidy of $45/ household/ year is applied to increase the NPV of the project to zero over the lifetime of the project.

	Break-even Tariff		Tariff with Gov. Subsidy	
Project NPV	$	-	$	-
# Comm. / Ind. Customers		19		19
Comm. / Ind. Tariff	$	0.52	$	0.40
Comm. / Ind. Sales	$	35,975	$	35,975
# HH Customers		764		764
HH Tariff	$	0.52	$	0.40
HH Sales	$	110,021	$	83,960
HH Subsidy Per Year	$	-	$	45
Total Subsidy / Year	$	-	$	34,582
Total Annual Revenue	$	145,995	$	145,995

Table 7. Mini-grid Project Engineering Design and Financial Summary

5.2.3 Mini-grid Pro-Forma Income Statement

The detailed income statement/pro-forma corresponding to the Break-even Tariff is included as Table 8. A post-design financial analysis such as this is absolutely necessary to define a financially sustainable mini-grid project. Computer-based tools for mini-grid design greatly facilitate the task of planners, allowing for an iterative process between the physical design process and the financial analysis. The planner is able to adjust the reliability level, consumption limits, tariff cross-subsidization, project lifetime and other factors until a truly sustainable project is achieved.

The pro-forma income statement displayed in Table 8 below details the cash flow for the first eight years of mini-grid operations. This financial model projects 25 years of operations, but only the first eight years of operation are displayed in the table.

PRO - FORMA INCOME STATEMENT

Timeline									
Calendar year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Revenues ($k USD)									
Operating Revenues									
Sale of electric power ($k USD)	-	153.3	161.0	169.0	177.5	186.3	195.6	205.4	215.7
Other revenue ($k USD)	-	-	-	-	-	-	-	-	-
Gross Revenue	-	153.3	161.0	169.0	177.5	186.3	195.6	205.4	215.7
Cost of Goods Sold ($k USD)									
Production Costs									
Fuel	-	35.4	37.1	39.0	40.9	43.0	45.1	47.4	49.7
Overhead Costs									
Labor	-	8.5	8.9	9.4	9.8	10.3	10.9	11.4	12.0
Cost of Goods Sold	-	43.9	46.0	48.4	50.8	53.3	56.0	58.8	61.7
Gross Profit	-	109.4	114.9	120.7	126.7	133.0	139.7	146.7	154.0
Operating Expenses ($k USD)									
O&M Generation	-	3.6	3.7	3.9	4.1	4.3	4.5	4.8	5.0
O&M Network	-	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2
Depreciation and Amortization	-	54.7	54.7	54.7	54.7	54.7	74.2	74.2	74.2
Other expenses	-	-	-	-	-	-	-	-	-
Total operating expenses	-	59.1	59.3	59.6	59.8	60.1	79.9	80.1	80.4
Net Operating Income (EBIT)	-	50	56	61	67	73	60	67	74
Interest income/expense	-	(40)	(38)	(36)	(34)	(32)	(30)	(28)	(26)
Non operating income	-	-	-	-	-	-	-	-	-
Pretax Income	-	11	18	26	33	41	30	39	48
Net Income									
Tax	-	2	4	5	7	8	6	8	10
Net Income	-	9	14	20	27	33	24	31	38

VALUATION (DCF)

Timeline									
Calendar Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Free Cash Flow									
EBIT * (1 - tau)	-	40	44	49	53	58	48	53	59
+ Depreciation	-	55	55	55	55	55	74	74	74
- CAPEX (w/ inflation)	547	-	-	-	-	195	-	-	-
- ΔNWC	2.9	30.8	1.7	1.8	1.9	2.0	2.1	2.2	2.3
Free Cash Flow	(549.86)	64.14	97.46	101.79	106.33	(84.17)	120.01	125.27	130.79
Discounted Cash Flow									
Discount factor	1.00	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34
Discounted cash flows (FCF)	(549.86)	55.96	74.17	67.58	61.58	(42.53)	52.90	48.17	43.87
PV of FCF	(0.00)	**IRR (FCF)**		**13%**					
PV of Perpetuity	-								
Total NPV	**(0.00)**								

Table 8. Mini-grid Project Pro-Forma / Income Statement (only the first eight years of operation are shown)

As mentioned above, all future cash flows are discounted at a weighted average cost of capital (WACC) of 14.63%. The effect of this discounting on future cash flow is highlighted in Table 8 under Valuation (DCF) – Discounted Cash Flows. Due to the high discount rate, cash flows in future years are heavily discounted to the present value. However, this is counteracted by an assumed inflation rate of 5.0%. With an assumed inflation rate of 5.0%, the revenues, fuel cost, overhead cost, and operating expenses grow accordingly each year. Due to rising cost and expenses each year due to inflation, it is crucial that the mini-grid operator also increases tariff rates appropriately. The annual increase in tariff is incorporated into the financial model and results in higher levels of nominal sales each year.

Earnings Before Interest and Tax (EBIT) or Net Operating Income, is used as the basis for the project free cash flow. A 20% tax (represented as Tau) is removed to account for corporate taxes. Depreciation is added back to the free cash flow since depreciation is an accounting expense included as an operating expense in the income statement.

Capital expenditures (CAPEX) on assets such as solar photovoltaics, batteries, distribution network, and other generation assets are captured below under the free cash flow calculation. These asset investments typically appear on the balance sheet and are only captured on the income statement in the form of depreciation. However, since these asset investments represent actual outgoing cash flow for the project, these investments are included in the free cash flow calculation below.

The change in net working capital (NWC) required to operate the mini-grid is then subtracted from the free cash flow. In this model, working capital is dominated by accounts receivable (late bills or customer credit, assumed to be 20% of annual sales) and inventory on hand (a 1 month supply of diesel fuel). It is important to note that interest expense for loans, although present on the income statement, is not included in the free cash flow. The use of a weighted average cost of capital (WACC) includes the cost of capital for both the debt and equity.

6. Utilization of REM

REM is very versatile. With REM the planner can address electrification cases ranging from the off-grid supply of a small village with only tens or a few hundred customers to the master electrification plan of an entire province, state or country. REM can work at the maximum level of spatial (i.e. customer or building), temporal (i.e. hourly patterns of demand or solar irradiation) and utilization (i.e. different customer types) granularity. If necessary to mitigate the computational burden, REM could also aggregate the individual demands into clusters, although so far this possibility has not been used in practice.

This ample and flexible level of granularity, the optimization approach (total supply cost minimization subject to diverse incentives and constraints that include explicit treatment of reliability or limitations in the use of certain fuels or technologies), the sophisticated engineering design capabilities (choice of generation dispatch strategies, physical constraints of power flows, use of actual catalog of existing components, or compliance with grid codes), and the comprehensive output capabilities (detailed generation design, dispatch and reliability analysis, lines and transformers layout, and summary reports with breakdown of costs and bill of materials) allows REM to offer an ample range of possibilities for governments, electrification agencies, distribution companies, investors, donors, cooperation institutions, regulators and policy-makers.

The human planner is the final decision-maker. REM is just a powerful tool to help in the electrification planning process. This section shows how REM, with its number crunching capability, can explore how the supposedly optimal plan would happen if some of our input data and assumptions were wrong. How REM can be adapted to meet requirements of users working under specific constraints. How the static plan that REM provides – i.e. the optimal power system design for a given future snapshot scenario – can be transformed into a implementable plan consisting of projects that are developed during a time period. How REM can support a diversity of regulatory and policy decisions. This is what has been done with REM so far and what could be done with the current version of REM. It is also described what could be possible to do with the ongoing enhancements to REM and others that are just planned to happen.

6.1. REM in a regional context

6.1.1. Sensitivity analysis

One of the most painstaking tasks of electrification planning projects is data gathering. In most planning projects a very substantial amount of effort is devoted to learn:

- the existing and forecasted layout and technical characteristics of the network,
- the location and estimated future demand patterns of a diversity of customer types,
- the technical performance characteristics and the cost of the physical electrification components, and
- the priorities, objectives and constraints of the institution that is ultimately responsible for the plan, so that these criteria can be implemented in the computer model.

Most of these input data, restrictions and assumptions are uncertain, and other can be inaccurate. Fortunately, once all the REM-required data has been gathered, REM allows to perform a comprehensive sensitivity analysis, exploring multiple scenarios based on variations of the input data set. The additional computer time is immaterial when compared to the effort devoted to data gathering, systematization, gap filling and assumptions. The planner can now evaluate how the initial plan responds to different "what if" questions.

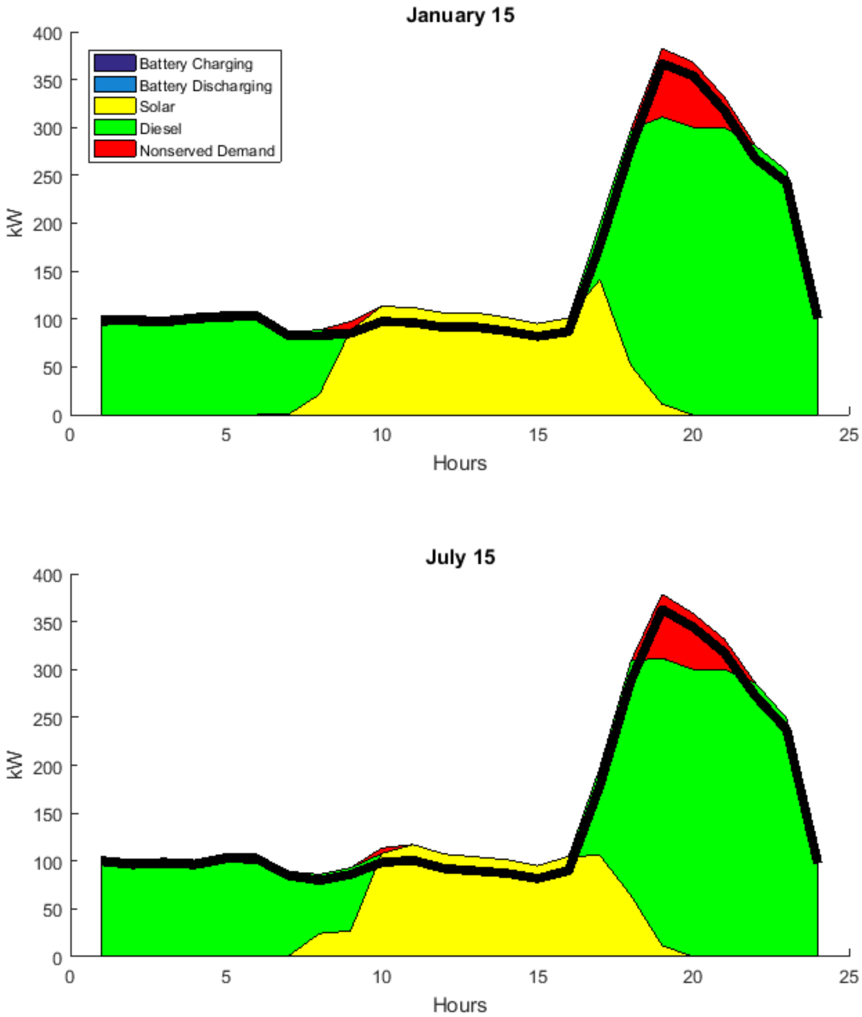

Figure 50: Daily sample dispatch with unconstrained diesel usage of a mini-grid with 5,000 demand profiles. The black line represents the total demand (critical plus non-critical).

<u>*Policy or regulatory preferences on technology options.*</u>

- Use of diesel, as an energy source for mini-grids and large isolated systems. Many jurisdictions ban or strongly limit the use of diesel for electricity production, because of multiple reasons (energy dependence, complex supply logistics, cost, theft and security hazards, maintenance requirements or environmental concerns). REM allows the decision-maker to introduce limits to the use of diesel (e.g. only as a back-up) and to examine the sensitivity of the reference electrification plan to diesel price. Figure 50 shows the dispatch for a couple of days in a mini-grid with 5,000 demand profiles with no limits to diesel usage (in contrast with the 30% limitation of the case example). In this scenario, the diesel generator serves 74% of the demand, only subject to economic criteria. The annual total cost per demand profile of this design is 62.28 $/yr, which is lower than the 63.02 $/yr of the base case (see Table 4). Note that the annual cost includes investment and operation of generation and networks, penalties for non-served energy and management cost; since diesel usage only affects the investment and operation costs of generation in mini-grids, the overall cost reduction is quite remarkable.

- Pre-established minimum goal for the grid extension share. REM calculates the optimum (least-cost) share of grid extension, mini-grids and standalone systems for a specific scenario, but the policy-maker may want to reach a certain target that might be above or below this optimum mix because of reasons other than cost.
  - Full Grid Extension: The optimal plan can be compared with one where every customer is connected to the grid. This allows to quantify the savings of the optimum mix as compared to the traditional grid extension approach. REM can be forced to connect every single load (perhaps excluding those very small and isolated). An example of this scenario is shown in Figure 51, which can be compared with the optimal one in Figure 41 and has an extra cost of approximately 13.5%.

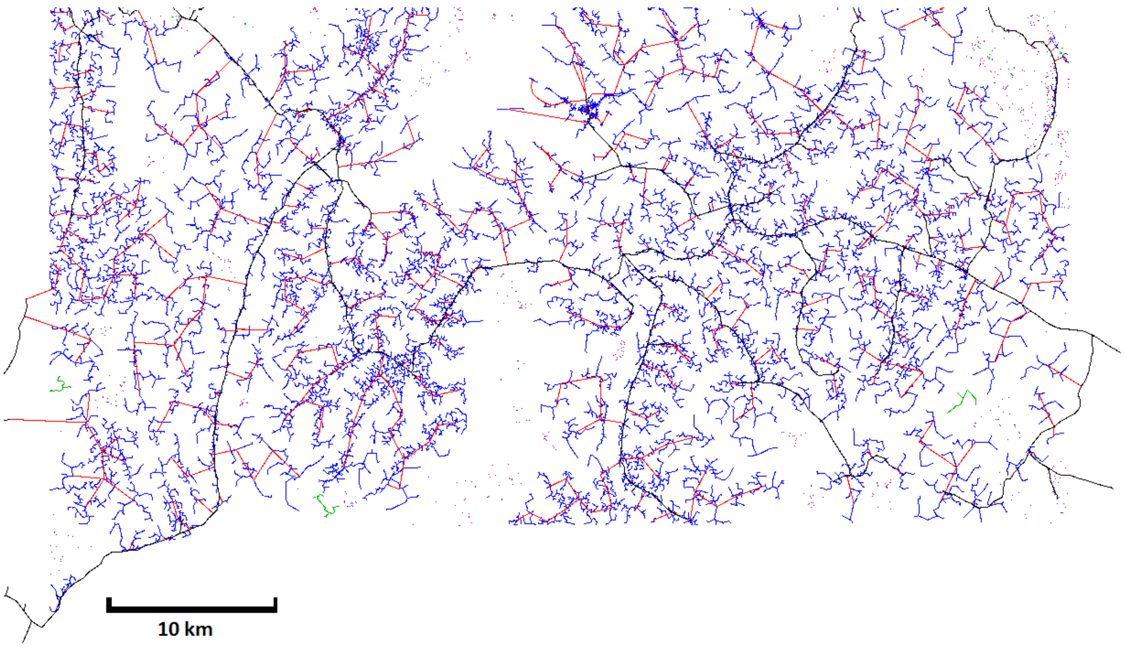

Figure 51: Full grid extension solution

  - Full off-grid scenario. The policymaker may want to explore the technical and economic consequences of complete off-grid electrification with mini-grids and standalone systems. This might be in fact the best solutions due to external factors, such as the poor financial situation of the incumbent distribution company in a certain region, or perhaps a deficit of centralized generation. The solution of this scenario is shown in Figure 52, which can also be compared with the optimal one in Figure 41 and has an extra cost of approximately 8%.

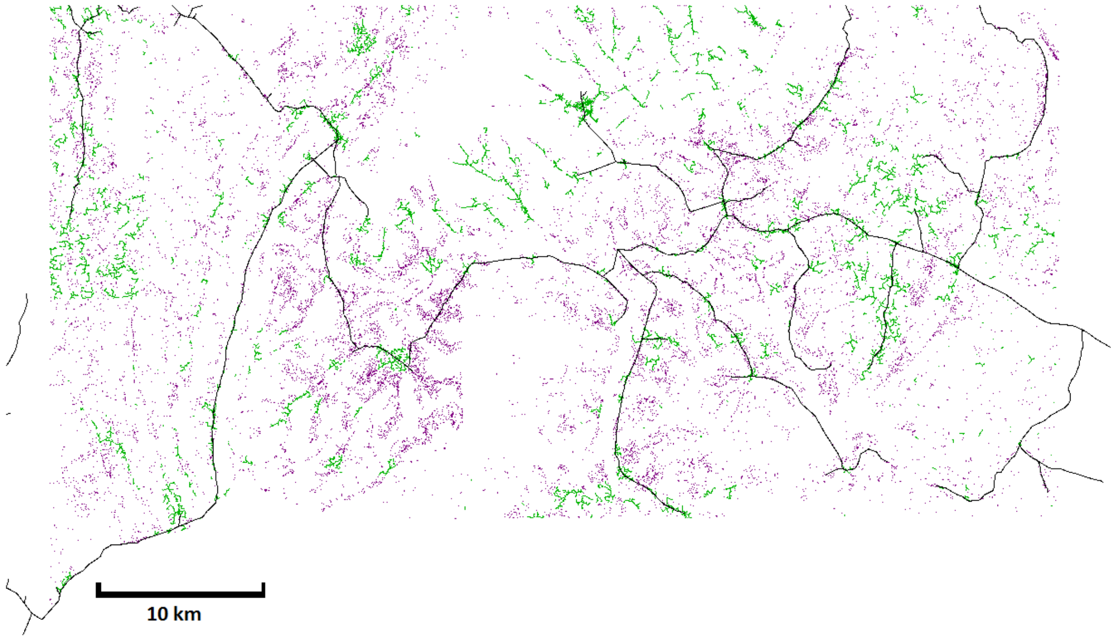

Figure 52: Full off-grid solution

   - Other particular scenarios. REM can calculate plans with prescribed on- and off-grid electrification shares, as determined by the policy maker, such as a scenario that meets a minimum or a maximum amount of investment available for grid extensions or mini-grids (or solar kits if that is the case).
- Choice of network catalogue and code: The decision maker may want to explore how the solution changes if a high-quality network is developed, or what is the impact of low-cost network alternatives (e.g. SWER and single-phase distribution lines as those established for the Brazilian "Luz para todos" strategy). REM allows the specification of different network catalogues and codes for grid extensions and mini-grids, as for instance including criteria to decide between overhead and underground lines in urban areas, or maximum voltage drop allowed for the supply of customers at the end of a line.
- Choice of off-grid generation catalogue and alternatives. REM calculates the cost of off-grid solutions (mini-grids or AC stand-alone systems) considering an input catalogue of components (batteries, solar panels, diesel generation, inverters, charge controllers) and system costs (installation, labor, operation and maintenance). The model can show the impact of choosing among different catalogue standards (e.g. low-cost/high-maintenance technologies vs. high-cost/low-maintenance alternatives) so the decision-maker can establish any technological standards that the developers should meet for any system installed in the country.
- DC Solar Kits. REM incorporates the possibility of supplying isolated customers with solar kits. This feature allows the planner to differentiate between small domestic customers (e.g. those below 20, 50 or 100 watts of peak load, including those with only two lights and a phone charger, or those which also can power small appliances) and possible large isolated customers (e.g. productive or community customers) that should still be supplied with "grid-like" AC stand-alone systems. A low-income residential customer provided with a solar kit receives a few hours of essential service for a fraction of the cost of a grid-connected customer, who on the other side has a (relatively) reliable 24x7 grid-service. REM allows pondering the different social costs,

and to classify consumers between solar-kit supply and grid-like service, therefore making possible the comparison between scenarios with different levels of penetration of solar-kits.

Sensitivity to demand levels.

Deviations in demand estimation for different types of customers, or in overall demand growth, might lead to very different planning results.

- Blanket approach. If there is no information about the diversity of the customers in a region, the decision maker might choose to provide them all with a prescribed minimum level of service (e.g. the SE4all Tiers, or a natural average customer profile extrapolated from close-by grid-connected populations). Figure 53 shows the electrification solution following this blanket approach (in this scenario we assume that all consumers are high-demand residential loads).

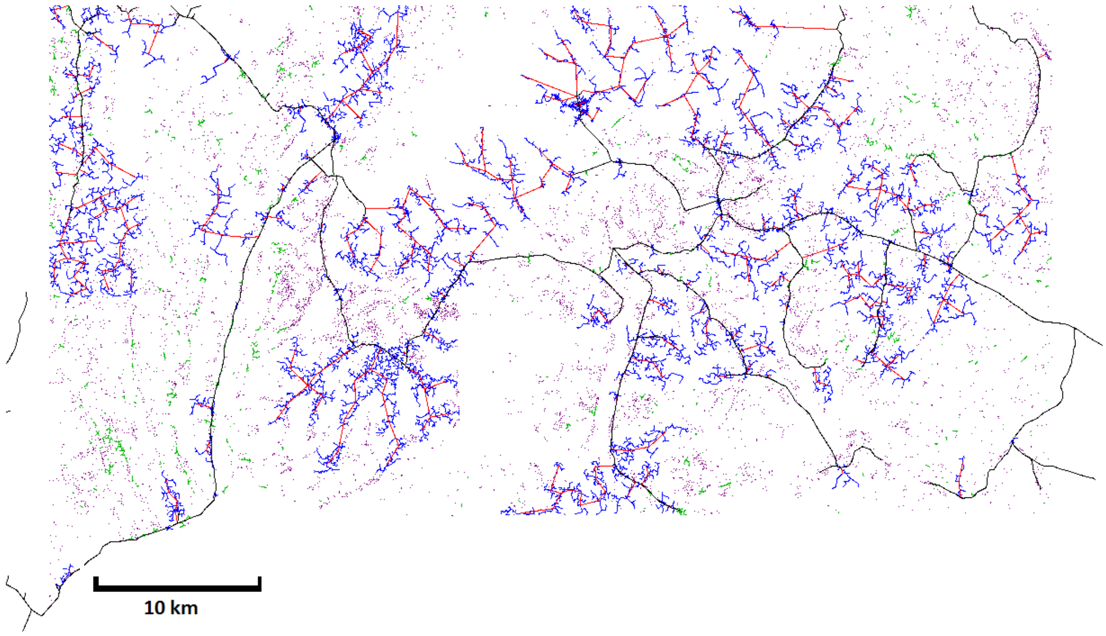

Figure 53: Solution assuming that all the consumers are of type 2 (higher-income households)

- Impact of anchor loads. The existence of large communal, commercial and industrial customers in a region has a very large impact on the electrification plan:
    - It may significantly modify the grid vs. off-grid balance
    - It may increase significantly the cost of network investment (since high-demand customers require more network capacity, as well as the generation equipment in case of off-grid solutions, but
    - It may lower substantially the average cost per energy unit (the equivalent cost per kWh) and the individual connection cost (per Wp) for all the customers in a grid (or mini-grid) that includes anchor customers.

  The scenario in Section 4 includes anchor loads (see Figure 41). With respect to this scenario, the planner may want to know how sensitive the plan to future demand growth; Figure 54 shows the solution when demand is double than expected. In this scenario the percentage of consumers electrified with grid extensions rises from 51% (case example) to approximately 73%, since the economies of scale related to extending the power grid outweigh the non-served energy cost caused by the 90%

reliability. Planners should carefully estimate the existence and location of these anchor customers (present or projected) in the planning area under study.

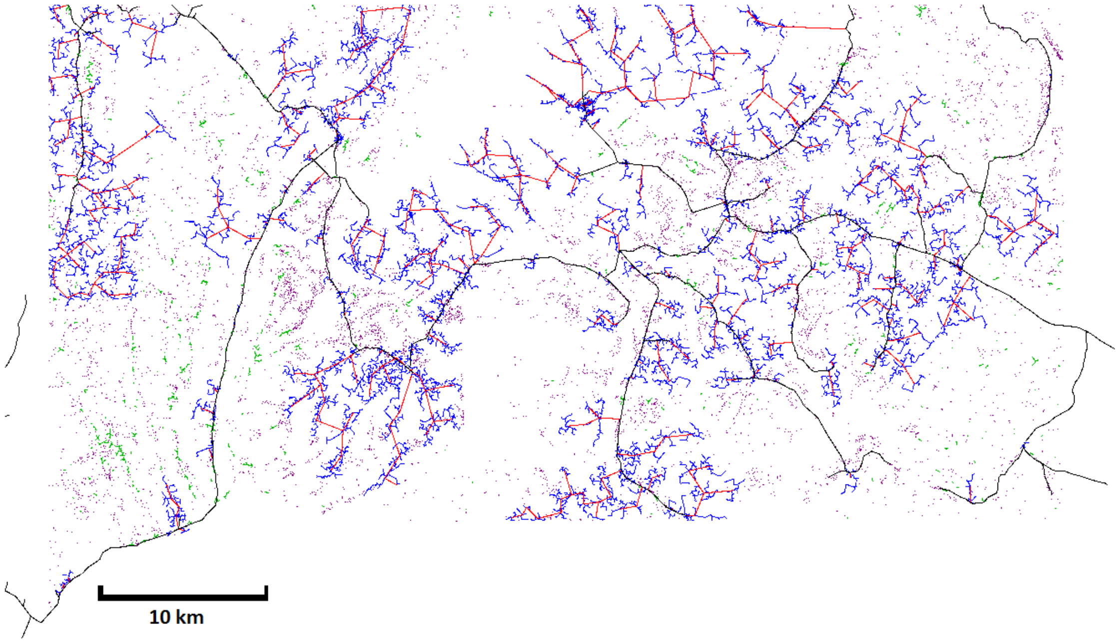

Figure 54: Solution assuming double-demand (for the 17 types of consumers of the case example)

Sensitivity to the cost of energy at central distribution level.

Decision-makers will also need to assess the impact of the price of wholesale energy on the electrification plan. Planning for a 2030 universal access target, or for any intermediate deadline, requires forecasting the wholesale energy price, which will depend on the future generation mix and the prices of fuels. A higher cost of energy supplied at medium or high voltage distribution level will obviously result in a lower share of grid extension solutions.

Sensitivity to reliability levels.

In REM, reliability is treated differently in grid and off-grid solutions:

- Grid reliability. Blackouts and load curtailments happen frequently in the distribution grid of many developing countries, especially in rural areas. Newly electrified population, even if located very close to the existing network, may prefer an off-grid supply if the main grid is very unreliable. On the other hand, when the main grid is very reliable, off-grid solutions only can compete costwise in isolated areas. REM can show how the grid/off-grid balance changes according to different reliability levels of the central supply, from a perfect 100% reliable grid service to highly unreliable systems; in our case example this is set to 90%, an average value found in some South-Saharan Africa countries. The impact of reliability depends of the chosen values of cost penalties for critical and non-critical non-served energy (CNSE) (see Section 3.3.6.2 for further details). Figure 55 shows the solution assuming that the reliability of the power grid is 100% instead of 90%. In this scenario, the percentage of consumers electrified with grid extensions rises from 51% (case example) to approximately 70%.

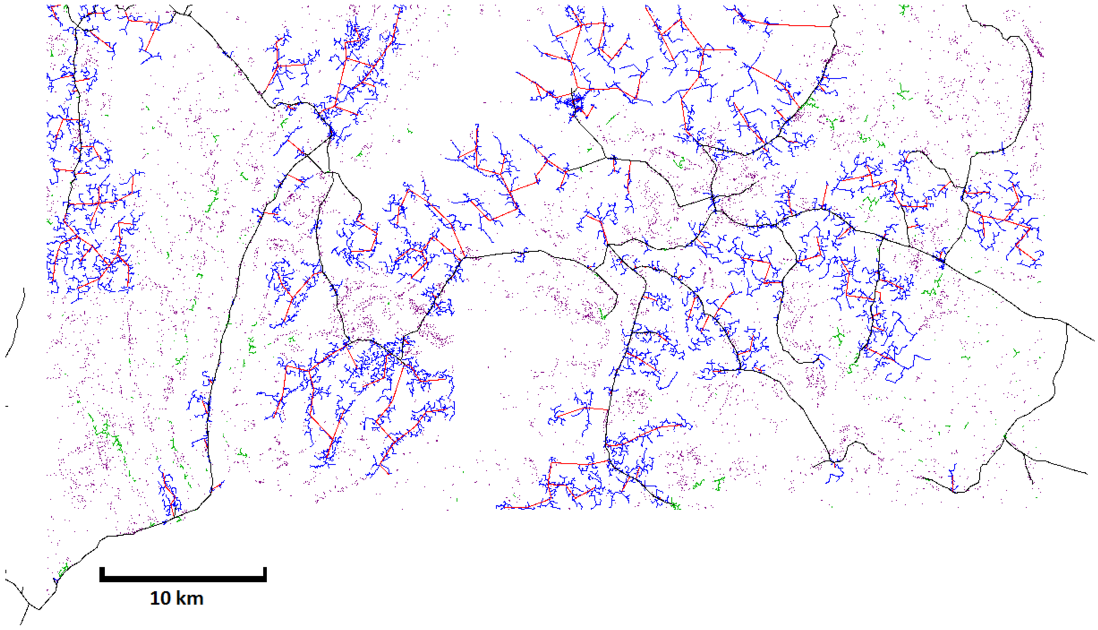

Figure 55: Solution for 100% grid reliability

- Minimum off-grid reliability. REM users may specify a minimum reliability target level to be achieved by mini-grids and standalone systems and/or set some values for the critical and non-critical costs of non-served energy (CNSE). The planner can use the CNSE values and the definition of the profiles of critical and non-critical load to represent the preferences of the consumers regarding their use of electricity, as well as the cost implications of their choices. Highly reliable off-grid generation systems are more costly, so the customers may prefer a less reliable system tailored to their needs or to their critical demand hours.

These are just some examples of the "what-if" questions that can be addressed by REM to support decision making. Carbon emissions, energy dependency (import of fuels), resiliency of investments (distributed vs. centralized systems) or financial constraints are other factors that, although not directly addressed by REM, may be translated to sets of REM input parameters, via social costs/penalties and explicit constraints.

6.1.2. Specific design requirements

When REM has been applied to support actual electrification planning processes, frequently some modifications of the original algorithms have been necessary to adapt to the specific characteristics of the problem. Some of them are:

- Administrative constraints on clusters. Administrative boundaries can have an influence on the final mix of delivery modes, the physical network layout and other characteristics of the plan (see section 3.2.6.). For instance, the policy maker might require that all customers within the boundary of a village or a district be supplied with the same delivery mode, although the REM least cost solution might result otherwise. This decision implies an increment in cost, but it may facilitate implementation and avoid social conflicts.
- Utility in a box. REM optimizes the minigrid generation considering different sizes of PV panels, batteries, diesel generators and other components, resulting in a variety of designs, each one tailored for a particular cluster. The "utility in a box" approach considers

that every minigrid has a specific standard design, pre-installed in a “box” or container that could be deployed, operated and maintained in a standard way. The goal is minimizing the distribution, operation and maintenance costs of the generation sets. In this case REM only supplies off-grid clusters with a single box, and the clustering process groups consumers accordingly, seeking aggregated demands that approximately match the capability of the box - or maybe of multiple boxes of standard sizes. The “utility in a box” approach might be tailored to add some degree of flexibility to the design (e.g. variable panel sizes or additional standard battery racks).

6.1.3. Temporal implementation strategy

REM is a static model that provides the optimal electrification plan for a prescribed future demand level, which in principle corresponds to some future date (e.g. 2030 for Universal Access in the Sustainable Development Goals). The planner can make use of the detailed output information of REM to design a temporal investment trajectory leading from the present moment to the target date.

REM output is detailed down to a number of individual lots or electrification projects. Solutions may range from one mini-grid design up to tens of thousands of grid extension and mini-grid lots in a national electrification plan, as well as many standalone solutions (solar kits or AC systems) for isolated customers.

This level of granularity allows the planner to decide how to prioritize the different lots, for instance according to:

- Annual investment budget available (overall, or specific for grid extension, mini-grids or stand-alone systems).
- Existence of community or productive loads. The planner might want to prioritize those grid extension or mini-grid lots with critical community services (e.g. hospitals or schools), or with loads with a positive impact on some specific productive uses of electricity. Examples of productive loads are pumping stations, industries, mines, and telecom towers. These anchor loads could help to bootstrap the economic sustainability of the individual lot or of the power system as a whole.
- Maximization of universal access rate. The lots can be ranked according to the amount of customers electrified at a lesser cost, therefore prioritizing those grid extensions or mini-grids with a lower cost per connection.

REM, together with RNM can also help establishing an implementation strategy that achieves different levels up the electrification ladder in successive phases:

- First phase (initial universal access plan). Achievement of universal access, but limited to an initial level of supply in a first phase, adapted to the different residential, productive and community services, where mini-grids and off-grid systems will play a major role.
- Second and subsequent phases (enhanced electrification plans). Sustainable growth of the level of supply, as the demand, the economic development and the affordability rise. REM can help calculate the additional generation required in the existing mini-grids to address additional demand requirements. RNM will calculate the reinforcements in the network required by the additional demand, and where a formerly isolated mini-grid could now better be connected to the grid to satisfy this incremental demand, and at what cost.

6.1.4. Policy and regulatory support

The detailed output of REM can help in identifying, evaluating and supporting different regulatory and policy measures.

Perhaps the most significant contribution of REM to mainstream regulation of the provision of electricity access is an accurate determination of the cost of service of the different delivery modes for each considered scenario, and its breakdown into cost components at any required level of detail. Based on this information, policy makers and regulators can estimate the financing needs of a national electrification strategy or electrification plan, which is the first step for the corresponding allocation of resources (not only financial) to their implementation. Sensitivity analysis can be used by the planner, as indicated above, to search for alternatives to the initial plan provided by REM, in case that it does not meet what policymakers want in terms of cost, mix of delivery modes, fuel use or any other metric.

Establishing the cost of service is a major component in determining the viability gap, i.e. the difference between the cost of service and what the beneficiaries of the service are willing to pay. The quantification of the viability gap for different scenarios is necessary to establish a financing scheme for the plan.

Once the cost of service and the viability gap have been estimated, it is possible to define sustainable tariffs and targeted subsidies for different customer types aimed at enabling universal electricity access at national level within an acceptable time range. An economically sustainable plan requires the viability gap to be filled by combinations of direct or cross subsidies and grants by the national budget, contributions to an electrification fund or international agencies and donors. Eventually, the revenues from the collection of electricity bills, including any cross-subsidizations at local or national level, should suffice to cover the future total costs.

Nevertheless, REM does not only help in estimating electrification costs. It can also facilitate a deeper insight regarding many relevant key factors in the complex task of formulating an electrification plan: quality of service, use of fuels and renewable mix, impacts on other policies such as promotion of productive activities, education, health, and others.

6.1.5. Future enhancements to REM

Despite its strong present capabilities – already tested in actual electrification plans – REM is still in the midst of a process of development and improvement. These are the major shortcomings of the model as it stands now:

Off-grid generation sources.

Mini-grids can only be supplied by solar PV and thermal generation (only diesel so far, which can be easily extended to other technologies). Work is ongoing to add wind generation and mini-hydro. The model makes use of batteries as needed to minimize cost and to satisfy reliability requirements.

The current version of REM assumes only one generation site in each mini-grid. This is a reasonable assumption when examining a large region with the purpose of identifying the delivery modes that result in the least cost solution. However, this could be a limitation when

REM is applied to the detailed design of a specific mini-grid, or if existing generation sources have to be included in a local design.

Top-down clustering

As explained in section 3.4.2.3, a new version of the clustering algorithm has been developed and is being tested and compared with the current bottom-up algorithm. They can complement each other, and it is possible that each one of them will have some advantages for different kinds of electrification problems. Stay tuned.

Existing LV lines.

The information usually available from the incumbent distribution company only includes the MV network and the existing MV/LV transformers, but not the LV network or the location and demand data of the grid-connected customers. Based on assumptions on the buildings/customers that are electrified, the current version of REM only addresses the supposedly non-electrified customers and assumes that any existing LV lines cannot be extended to connect any non-electrified customers. Therefore, when REM decides which delivery mode to use, for the grid-extension option REM only extends the existing MV network and designs new LV lines and MV/LV transformers to connect the non-electrified consumers, but it does not try to make use of the existing LV lines and transformers. Assuming that the existing LV network is close to saturation or too far from the unelectrified customers can be a reasonable assumption, but improvements are possible.

Upstream network and generation reinforcements.

REM decides among the three delivery modes on the basis of cost minimization. In the case of grid extensions, besides the cost of extending the MV/LV network and the cost of any needed transformers, REM accounts for the cost of the extra wholesale energy that has to be delivered. The "wholesale energy price", for the period of interest of the planning exercise, must be estimated with information provided by the incumbent distribution company and the regulator. If this price is computed properly, it must include the bulk energy price at the transmission network level (this price may include components of ancillary services, firm capacity remuneration mechanisms and other generation related charges), the transmission network charge, and the HV and MV distribution system charges. Depending on how tariffs are computed, other regulated charges and taxes may be included here or charged separately. The current version of REM applies this "wholesale energy price" – which accounts for more components than just energy- as follows:

- It could be defined either uniformly throughout the MV for all the grid-extension connections, or different for each particular MV segment of the existing grid (types of segments)
- Invariant with respect to the quantity of energy served. This means that all the components of the price are proportional to the quantity (constant in p.u.)

This approach can be improved by noticing that, in some cases, the cost of the upstream infrastructure is not linear with respect to the extra energy delivered. On one hand, the existing infrastructure may have some capacity margins left, so that upstream costs grow less than expected. On the other hand, in some cases the required reinforcements may be far more expensive than the current per-unit costs.

This reasoning applies to the HV distribution network, the transmission network and the bulk generation, which, for substantial increases of the new connected demand may need to be upgraded. The difference is that the average value of the "wholesale energy price" is an excellent approximation when REM tries to decide whether to connect a cluster or to leave it as a mini-grid, while MV network reinforcements have a very strong local component. In any case, upstream reinforcements at all levels MV, HV, transmission and bulk generation – have to be incorporated into a comprehensive electrification plan.

The research team at the MIT/Comillas Universal Energy Access Laboratory is actively working on the enhancements to REM and the additional modeling efforts that are needed to adequately address these issues.

Transmission reinforcements and new generation investments have to be dealt with separate models. Regarding a more detailed treatment of the reinforcements of the distribution grid, a brownfield RNM will be applied. The brownfield RNM requires as input the existing grid, the existing demand, and the additional clusters of customers to be supplied (with their demand and their location).

Inputting an actual distribution grid (and the current demand in detail) is a process that usually requires intensive data debugging. The data of the existing grid has to be correct in terms of format, parameter values, connectivity and power flow calculations. In order to facilitate this process, it is being developed a simplified format, based on tables which describe the consumers (or prosumers), the electrical nodes, the power lines and the transformers. To avoid inputting the information of every element, a catalog of components is also being used. The data format is designed to provide a complete description of the distribution network, while minimizing data requests. When these developments are complete, the model will be able to calculate not only the cost of grid extensions, mini-grids and stand-alone systems, but also the required reinforcements in the distribution grid. The following steps will be to develop tools to estimate reinforcements in the transmission grid, and the installation of additional generation capacity in the country.

6.2. In a local single cluster context

The majority of the data required to execute REM in a regional or national context are identical to the data required in a single mini-grid study, however, the purpose of the study is often different. When REM designs a single mini-grid for a collection of potential customers, additional design requirements can be specified (e.g. the poles and wires must be placed along streets, roads or paths within villages). Specific questions can be addressed that are irrelevant when REM is used to determine the best mix of delivery modes in a region (e.g. the design of sustainable financing schemes, as explained in section 5.2).

When used by rural electrification practitioners developing mini-grid projects at single village or community level, REM offers distinct benefits and capabilities:

1) Simulation of different operation strategies, from simple heuristic rules to predictive-based optimization
2) Determination of the type and size of equipment for generation, energy storage and demand management (including deferrable loads such as pumps and heating/cooling loads) to achieve minimum cost of supply;

3) Integration of the design of the distribution network into the overall mini-grid optimization.

As previously explained, the standard mini-grid design includes specific details on the generation and network components of a mini-grid:

i) A graphic layout of the network in the form of a kml file, along with a table specifying the different wires to be employed, with their name, number, length, capacity limit and cost, as well as the transformers;
ii) The optimal configuration of generation and storage assets, their investment costs and their dispatch profile, plus the management (labor) and O&M costs and the cost of non-served energy;
iii) A bill of materials as needed for the electrification project.

REM can be used to perform sensitivity analysis for parameters such as diesel price, percentage of renewable generation, estimated demand, reliability of main grid supply, or dispatch strategy.

REM can make use of several dispatch strategies, such as load following or cycle charging, to determine the most cost-effective approach. Since the model is able to take in the individual demand for each customer, REM uniquely allows for the study of scenarios with higher productive loads. For instance, this assists in understand the effect of promoting certain type of load growth in a community. Business models for mini-grids that are based on an anchor load such as Telcom towers can be studied to understand their commercial viability.

Another clear application of REM is to facilitate the financial analysis of mini-grid projects, as described in section 5.2. Coupling LREM with a project finance analysis spreadsheet allows the planner to iterate between both technical and policy design, conveniently modifying the financial approach and the input design parameters until a financially sustainable model is obtained.

6.2.1. Understanding the cost structure of mini-grids.

Once the input data for a cluster of customers are obtained, there are different types of analysis that can be performed with REM to get insights on the trade-offs that are embedded in the minimization of costs in the design of a mini-grid. A detailed cost analysis at customer level is possible with the help of REM, explicitly including generation, network and other costs in the evaluation.

In Figure 56 all customers in the mini-grid have been placed in descending order according to their annual consumption. Successive mini-grids have been designed, adding one customer for each successive design. The additional cost of adding a new customer has been computed and broken down into its three major components: generation, network and management costs. The process is continued until all customers are connected to the complete mini-grid. If customers have identical consumption levels, such as residential customers, they have been ordered according to their distance to the generation site. Note in the figure that this does not necessarily mean that the network costs will be monotonically decreasing. These marginal cost depends on the prior network layout, and the network extension process is in general a very nonlinear process.

For the large energy consumption customers (e.g. commercial customers) at the left side of the figure, the network cost and management cost as a fraction of total cost are nearly insignificant on a per unit basis relative to the energy cost. However, for the residential customers (right side of the figure, i.e. low energy consumption), the network cost and management cost have more weight relative to the total cost. This is due to the lower total kWh consumption of the residential customers. These customers still incur a fixed network cost and management cost, which remains significant when analyzed on a per unit basis.

Despite these higher management and network costs for residential consumers, Figure Y1 indicates that 70% of the marginal cost of adding additional residential customers to the mini-grid is dominated by energy generation cost. The network cost incurred by each additional customer barely exceeds $0.10/kWh due to the compact building layout of the village. This network cost on a per-unit basis can be much higher for sparsely distributed mini-grids.

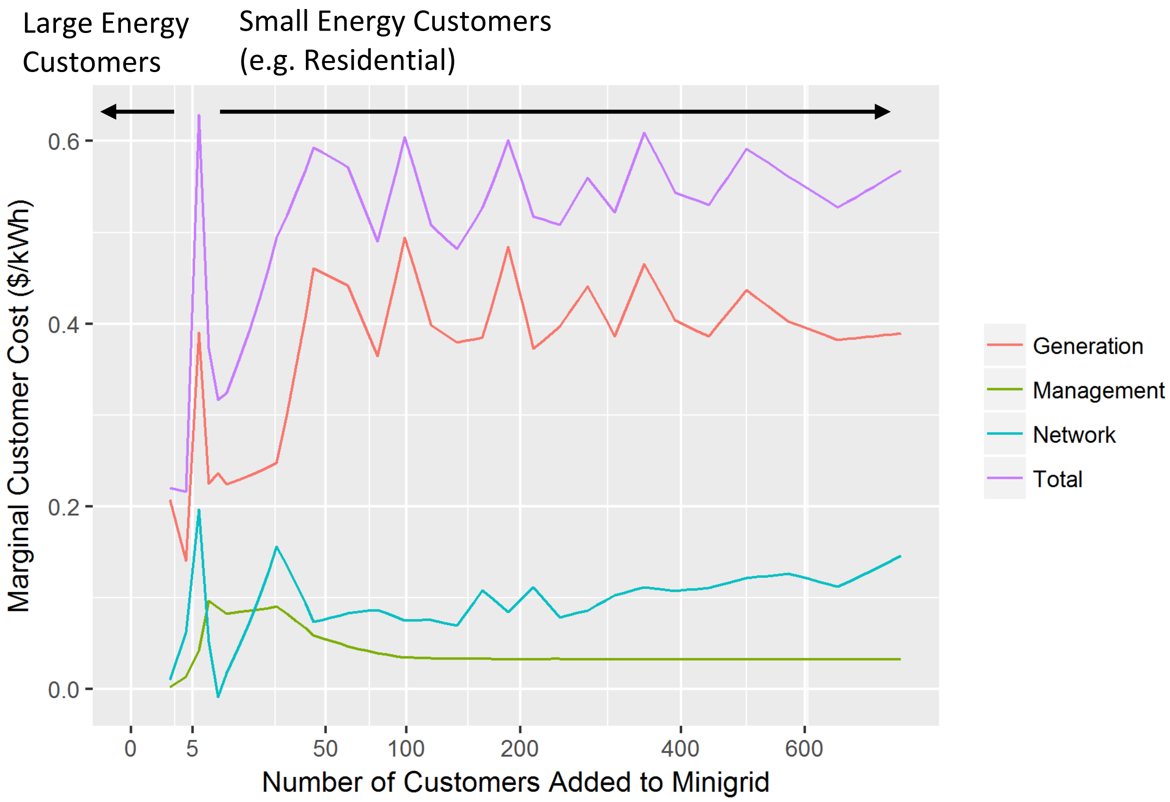

Figure 56. Marginal customer cost breakdown for Nigerian Mini-grid case study

The full project cost on a per kWh basis can be plotted geospatially to provide additional insight into the cost structure for the mini-grid project. In Figure 57 one can identify the lowest cost customers as the commercial customers (green). Leaving aside the large commercial customers, the next least expensive customers are found in the center of the village and then gradually diffuse outwards in layers. As it can be expected, the higher marginal cost customers are located on the fringes of the village.

The red ring of higher cost customers near the center of the village) is due to the discrete sizing of the diesel generators. As customers are added to the mini-grid, the generator sizing must be increased to meet additional load. The discrete sizing of the generator then results in ample diesel generation capacity to meet the required load, but forces the diesel generator to operate at lower efficiencies. The lower operating efficiencies result in higher generation cost for all customers, which is captured as a higher marginal cost for these few additional customers. This increased marginal cost is visible in Figure 56 above. The increases in network cost are due to the significant network reconfigurations required while the total customer count is low, and each additional customer results in significant network expansion.

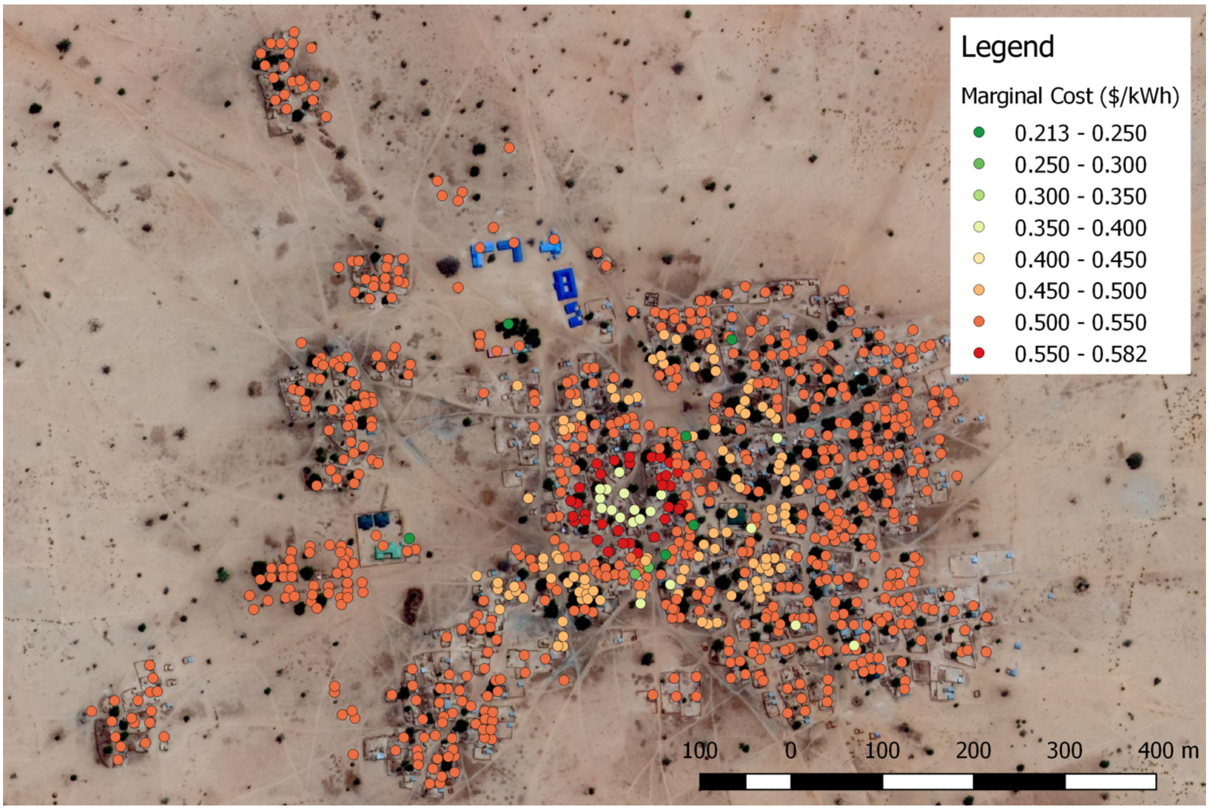

Figure 57. Marginal cost of service for Nigerian Village customers

6.2.2. Future enhancements to LREM.

Off-grid generation sources.

In this topic, LREM shares the same need for future enhancements that was described for REM in section 6.1.5.

Double check the cluster definition.

The input data to design a mini-grid may contain customers that are too far from the rest of the cluster so that it does not make technical or economic sense to connect them to the mini-grid. In this case, a standalone system might be a better solution, or even separate mini-grids. LREM might make use of the new top-down clustering algorithm in REM to verify if some customers should be disconnected before proceeding with the mini-grid design.

Getting closer to the construction project specification.

REM was not initially designed to provide an electrification plan at the level of detail necessary to specify a construction project. The present version of REM has moved one step ahead in this direction by introducing the RNM option of forcing the distribution lines to be located along the paths (roads, streets or simply trails or lanes) specified by the planner. The LREM developing team is currently working on adding and optimizing the position of the poles and

MV/LV transformers, while considering the necessary wiring to properly connect the individual buildings.

Financial analysis.

The standard financial analysis spreadsheet is being extended to account for the different possible viewpoints in the specification of a financially sustainable mini-grid: private developer, distribution utility, cooperative or rural electrification agency. Each one of these agents has different perspectives regarding the objective function, whom to connect, cross subsidization or the economic lifetime of the project.

7. Conclusions

Much has been said already and little is left to be added now. It can be concluded that the electrification access problem is huge, and that sound planning is absolutely necessary, since it is required to think big and vision and efficiency are of essence. Geospatial data and other digital information is becoming increasingly available and cheaper, as well as computing power, therefore making possible the use of advanced computer-based approaches to electrification planning. The model presented in this paper – the Reference Electrification Model, REM – represents the state of the art is this kind of tools, since it takes full advantage of the geospatial information and is able to work at the maximum granularity level in time (hourly demand, weather patterns, and supply reliability) and space (individualized supply to each building).

This is fortunate, since the results obtained so far with REM show that temporal and spatial granularity matters. The location of singular loads (i.e. schools, health centers, official buildings, small and large commercial and industrial loads such as trade centers or mines, etc.) and their consumption (and also production) patterns have a significant impact on the mix of delivery modes (grid extension, mini-grids and standalone systems) and geographical layout of the least cost plan.

In the same way that RNM was accepted by Spanish distribution companies and the Spanish regulatory authority as a benchmark for efficient design and operation performance, the purpose of REM is to be validated by multiple stakeholders and serve as the basis for collaboration towards efficient electrification planning.

REM is being used in the design of master national electrification plans in several developing countries, as well as to support ambitious mini-grid based electrification programs. REM is also being used to study the feasibility of novel approaches that aim at turning bankrupt incumbent distribution companies into economically viable business models. REM is still in the initial stage of utilization and it shows much potential as a support tool for a multiplicity of users. Stay tuned.

8. Acknowledgements

Many people and institutions have contributed to make REM a reality. The Enel Foundation, the MIT-Tata Center for Technology and Design and Iberdrola believed in this project when it only was a bunch of ideas and much enthusiasm. The bulk of the work during most of the last five years has been supported by the MIT-Tata Center. Additional funding has been provided by the Spanish National Plan of Research, Development and Innovation, General Electric, Shell, the World Bank and the German Corporation for International Cooperation GmbH (GIZ). The Shell Foundation has brought REM and our team to a new dimension in electrification planning, searching now for the electric company of the future in the developing world. Continuous support in many forms have been given by Praveer Sinha, Ganesh Das, and other numerous professionals from Tata Power Delhi, where a team is developing an industrial-grade interface of the REM model. We appreciate the time and dedication of the many professionals in electric utilities and ministries that have worked long hours with us providing the data needed to run the model. We have exchanged ideas and received useful feedback for so many experts that we cannot name them here. We are grateful to all of them.

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10. ANNEX. Case Results

This annex provides a more complete account of the final electrification results of the scenarios mentioned in Section 6 (sensitivities with respect to mandated grid connection, mandated off-grid solutions, high demand growth, higher-income-household demand for all consumers and fully reliable power grid). We also provide off-grid generation results of two scenarios (only renewable energies, where diesel is not allowed; and unconstrained diesel, where the diesel generator is allowed to serve 100% of the demand).

10.1. Final Electrification Results

This section shows the final electrification results of the scenarios mentioned in Section 6: sensitivities with respect to mandated grid connection, mandated off-grid solutions, high demand growth, high-demand residential consumption for all consumers and fully reliable power grid.

10.1.1. Full Grid Extension Scenario

Off-grid costs are significantly increased to produce a scenario where grid extensions electrify most consumers.

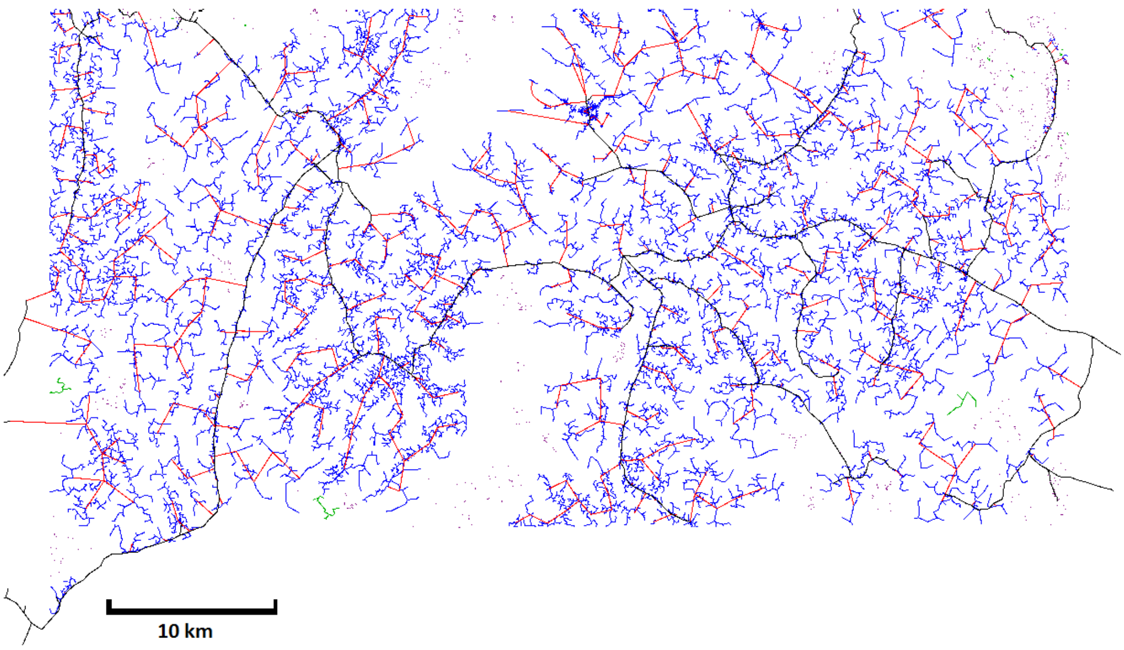

Figure 58: Full grid extension scenario. The MV existing power grid is represented with black lines.

Although a low percentage of consumers still have off-grid solutions, the total electrification cost (including investment, operation and a penalty for non-served energy) of grid extension designs is already larger than the total electrification cost of the case example shown in Section 4 (including mini-grids, isolated systems and grid extension designs). Table 9 provides a summary of the final electrification solution of the full grid extension scenario.

	Mini-grids	Isolated	Grid Extensions	All
Number of Customers	191	959	51,559	52,709
Fraction of Customers	0.00	0.02	0.98	1.00
CAPEX Per Customer ($/yr)	292.66	177.06	143.20	144.36
OPEX Per Customer ($/yr)	338.54	373.02	123.06	128.39
Non-served Energy Cost Per Customer ($/yr)	5.87	55.60	53.05	52.92
Final Cost Per Customer ($/yr)	637.07	484.73	319.31	323.47
Total CAPEX ($/yr)	55,898	169,796	7,383,183	7,608,877
Total OPEX ($/yr)	64,660	357,731	6,344,873	6,767,264
Total Non-served Energy Cost ($/yr)	1,122	53,316	2,735,003	2,789,441
Final Cost ($/yr)	121,680	464,856	16,463,059	17,049,595
Fraction of Demand Served (p.u.)	0.987	0.903	0.900	0.900
Cost Per kWh of Demand Served ($/kWh)	0.706	0.310	0.295	0.297

Table 9: Full grid extension scenario: solution summary.

Figure 59 shows the total system cost (per kWh of demand served) for grid extensions. As expected, the cost per demand served of grid extensions is much larger than in the case example.

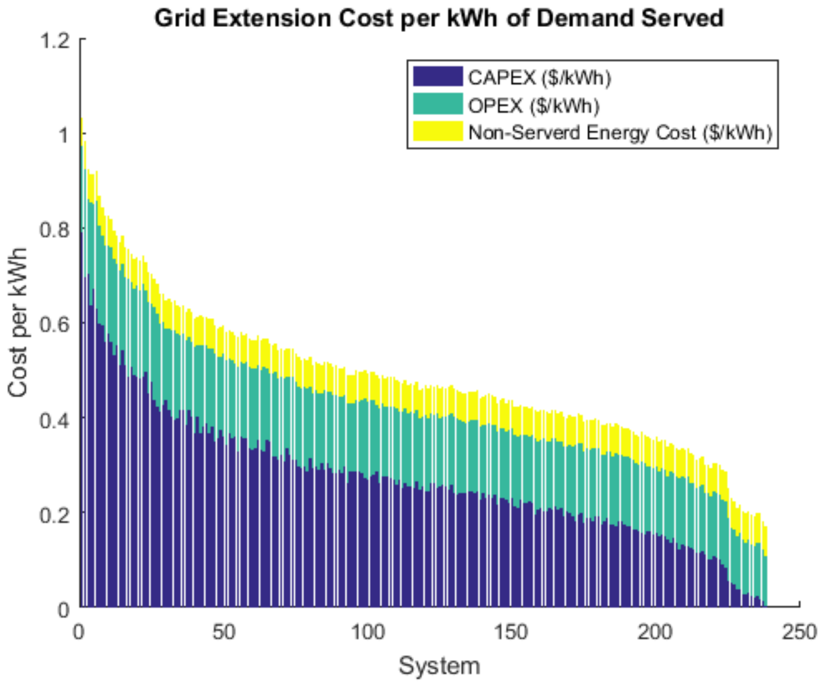

Figure 59: Total costs per demand served in different systems: investment, operation and non-served energy (full grid extension scenario)

Figure 60 presents a different cost breakdown to show the relative weight of generation, network and connection costs for different types and sizes of systems (management and non-served energy costs are not represented here).

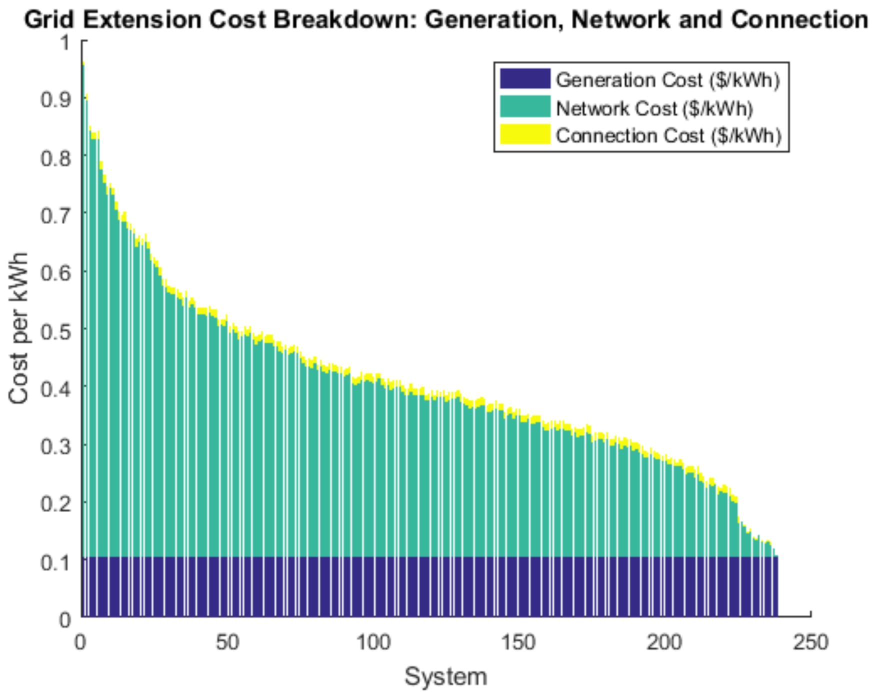

Figure 60: System cost per kWh of demand served: generation, network and connection (full grid extension scenario)

10.1.2. Full Off-Grid Scenario

The power grid reliability is significantly decreased to produce a scenario with only off-grid solutions.

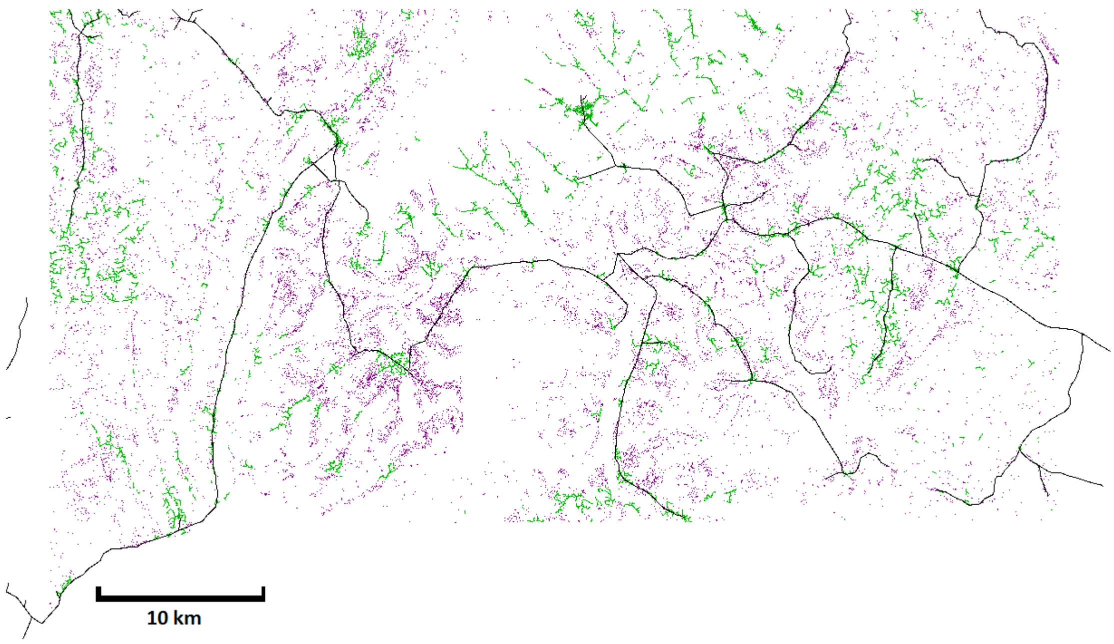

Figure 61: Full off-grid scenario. The MV existing power grid is represented with black lines.

Table 10 provides a summary of the final electrification solution of the full off-grid scenario.

	Mini-grids	Isolated	Grid Extensions	All
Number of Customers	30,212	22,497	0	52,709
Fraction of Customers	0.57	0.43	0.00	1.00
CAPEX Per Customer ($/yr)	206.93	230.32	-	216.91
OPEX Per Customer ($/yr)	56.47	72.79	-	63.43
Non-served Energy Cost Per Customer ($/yr)	6.14	56.25	-	27.53
Final Cost Per Customer ($/yr)	269.54	359.35	-	307.87
Total CAPEX ($/yr)	6,251,907	5,181,441	0	11,433,349
Total OPEX ($/yr)	1,705,930	1,637,483	0	3,343,413
Total Non-served Energy Cost ($/yr)	185,437	1,265,428	0	1,450,865
Final Cost ($/yr)	8,143,275	8,084,352	0	16,227,627
Fraction of Demand Served (p.u.)	0.985	0.932	-	0.959
Cost Per kWh of Demand Served ($/kWh)	0.284	0.273	-	0.279

Table 10: Full off-grid extension scenario: solution summary.

Figure 62 shows the total system cost (per kWh of demand served) for mini-grids.

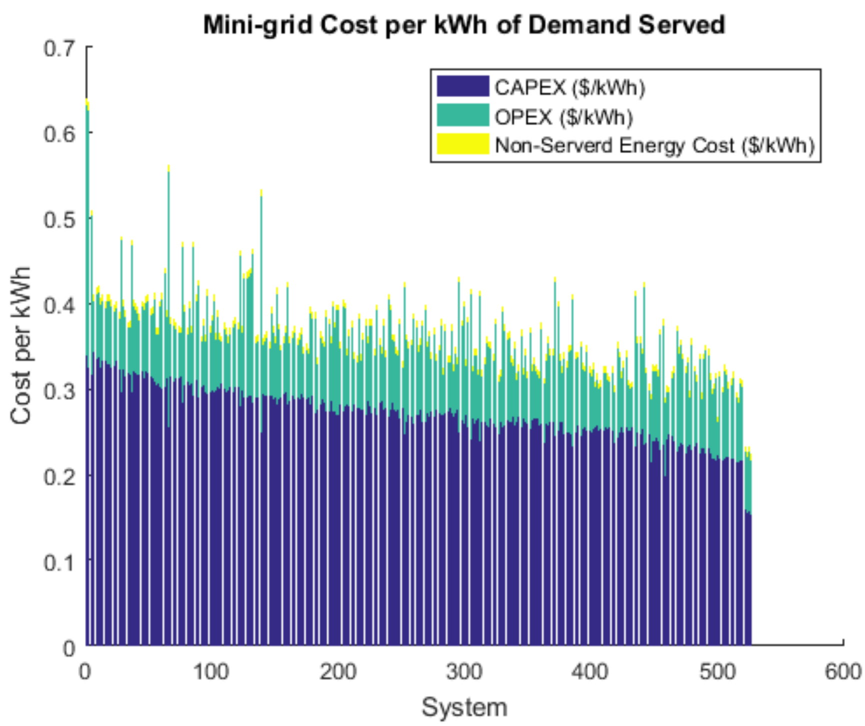

Figure 62: Total costs per demand served in different systems: investment, operation and non-served energy (full off-grid scenario)

Figure 63 presents a different cost breakdown to show the relative weight of generation, network and connection costs for different types and sizes of systems (management and non-served energy costs are not represented here).

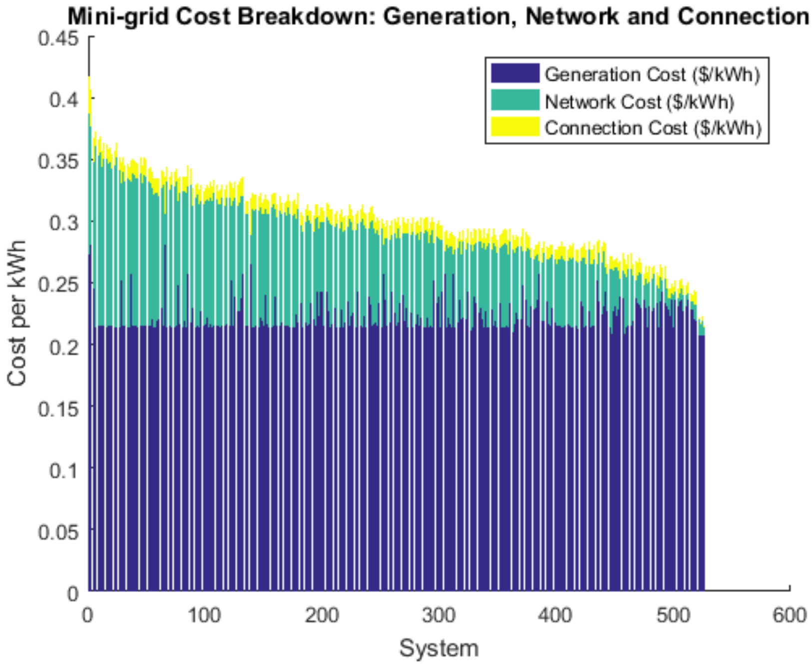

Figure 63: System cost per kWh of demand served: generation, network and connection (full off-grid scenario)

Figure 64 shows the total system cost per kWh of demand served for isolated systems.

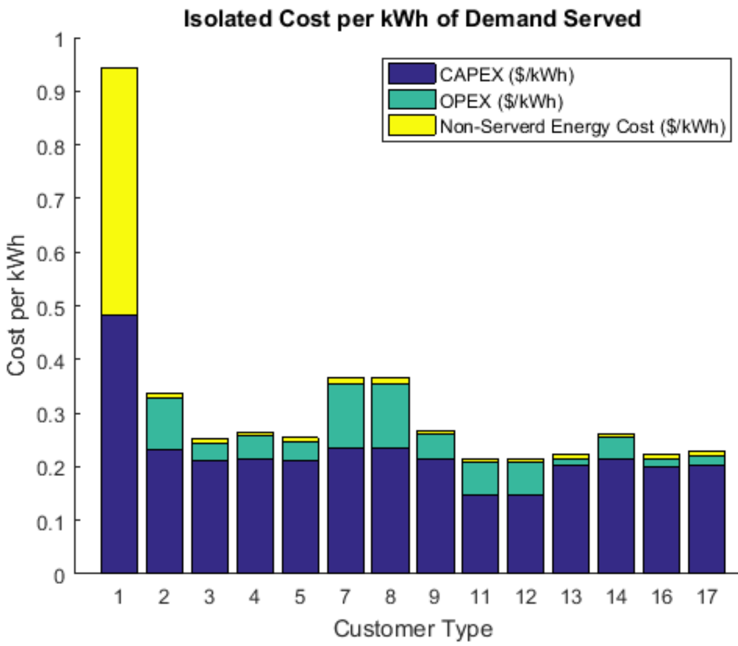

Figure 64: Cost per kWh of demand served of isolated systems (full off-grid scenario).

10.1.3. Higher-income-households scenario

In this scenario, all the consumers have the demand profile that corresponds to the higher-income household consumer (customer type 2) in the case example presented in Section 4.

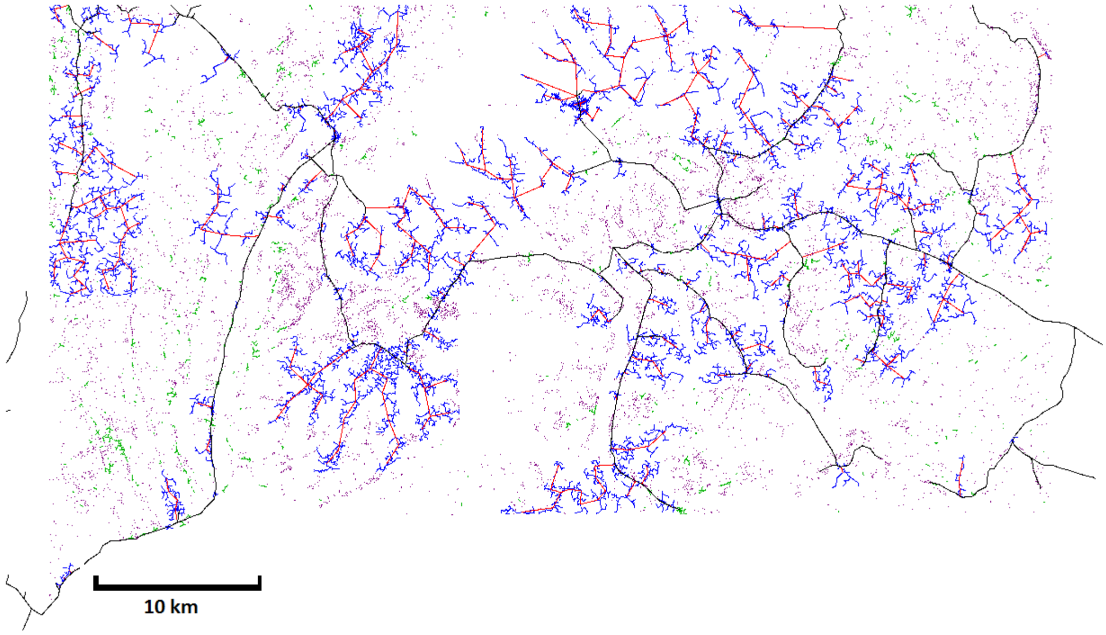

Figure 65: Higher-income-households scenario. The MV existing power grid is represented with black lines.

Table 11 provides a summary of the final electrification solution. Since there is only one customer type, all the isolated consumers are electrified with the same AC system, whose characteristics are provided in the "Isolated" column.

	Mini-grids	Isolated	Grid Extensions	All
Number of Customers	5,799	10,581	36,329	52,709
Fraction of Customers	0.11	0.20	0.69	1.00
CAPEX Per Customer ($/yr)	315.88	292.60	113.29	171.57
OPEX Per Customer ($/yr)	70.01	123.85	152.77	137.86
Non-served Energy Cost Per Customer ($/yr)	10.02	11.22	71.73	52.79
Final Cost Per Customer ($/yr)	395.92	427.67	337.79	362.23
Total CAPEX ($/yr)	1,831,816	3,096,028	4,115,645	9,043,490
Total OPEX ($/yr)	406,017	1,310,436	5,549,887	7,266,340
Total Non-served Energy Cost ($/yr)	58,133	118,731	2,605,875	2,782,739
Final Cost ($/yr)	2,295,966	4,525,195	12,271,408	19,092,569
Fraction of Demand Served (p.u.)	0.986	0.966	0.900	0.923
Cost Per kWh of Demand Served ($/kWh)	0.268	0.282	0.218	0.237

Table 11: Higher-income-households scenario: solution summary.

Figure 66 shows the total system cost (per kWh of demand served) for grid extensions and mini-grids.

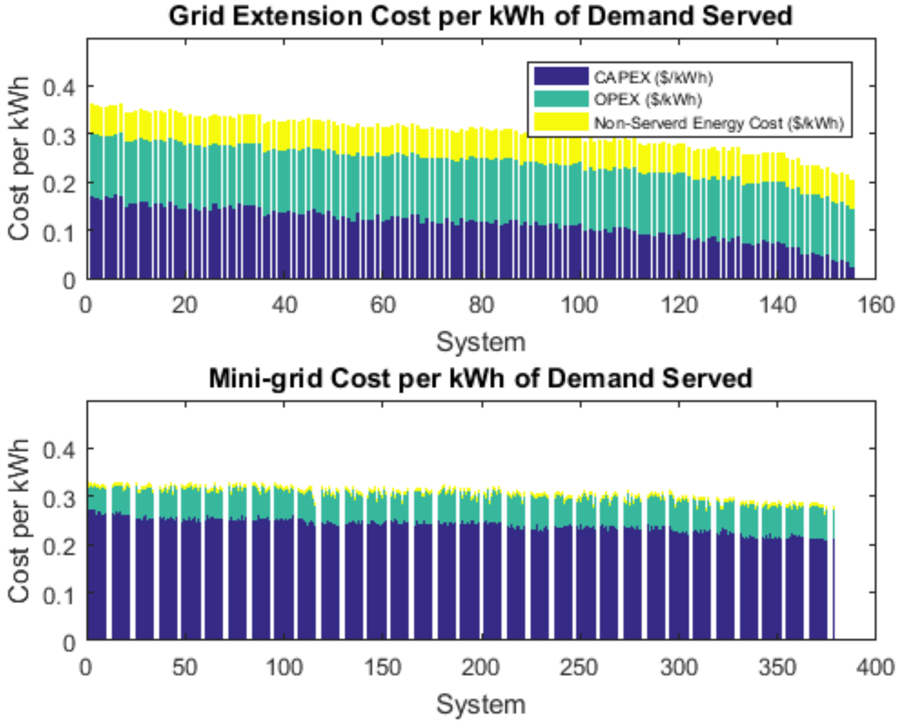

Figure 66: Total costs per demand served in different systems: investment, operation and non-served energy (Higher-income-households scenario).

Figure 67 presents a different cost breakdown to show the relative weight of generation, network and connection costs for different types and sizes of systems (management and non-served energy costs are not represented here).

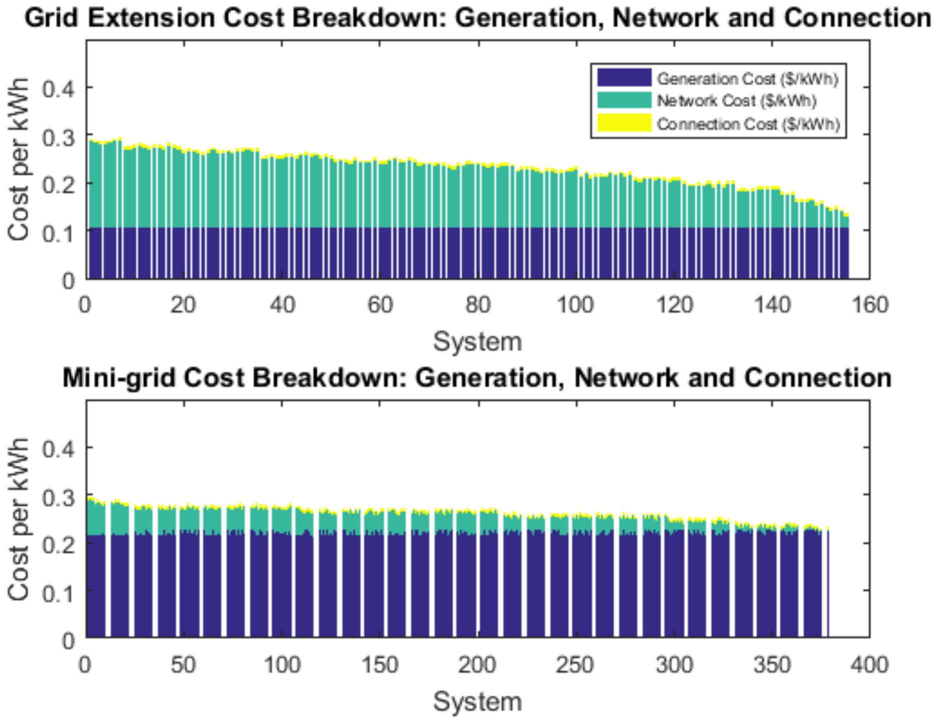

Figure 67: System cost per kWh of demand served: generation, network and connection (higher-income-households scenario).

10.1.4. High Demand Growth Scenario

In this scenario, all the consumers have duplicated the demand of the case example shown in Section 4.

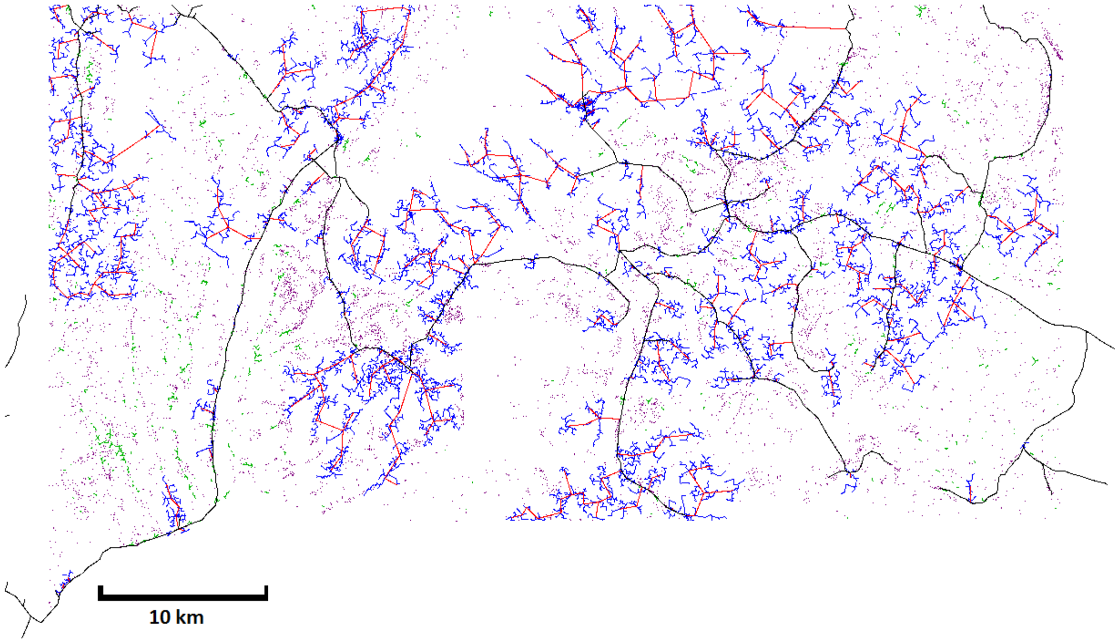

Figure 68: Higher-income-households scenario. The MV existing power grid is represented with black lines.

Table 12 provides a summary of the final electrification solution.

	Mini-grids	Isolated	Grid Extensions	All
Number of Customers	4,739	9,664	38,306	52,709
Fraction of Customers	0.09	0.18	0.73	1.00
CAPEX Per Customer ($/yr)	327.78	304.93	119.22	172.02
OPEX Per Customer ($/yr)	72.19	124.64	231.85	197.84
Non-served Energy Cost Per Customer ($/yr)	10.57	11.56	116.96	88.07
Final Cost Per Customer ($/yr)	410.54	441.13	468.03	457.93
Total CAPEX ($/yr)	1,553,341	2,946,872	4,566,844	9,067,058
Total OPEX ($/yr)	342,116	1,204,486	8,881,177	10,427,778
Total Non-served Energy Cost ($/yr)	50,105	111,674	4,480,306	4,642,085
Final Cost ($/yr)	1,945,562	4,263,032	17,928,327	24,136,922
Fraction of Demand Served (p.u.)	0.986	0.981	0.900	0.916
Cost Per kWh of Demand Served ($/kWh)	0.264	0.275	0.178	0.198

Table 12: Higher-income-households scenario electrification: solution summary.

Figure 69 shows the total system cost (per kWh of demand served) for grid extensions and mini-grids.

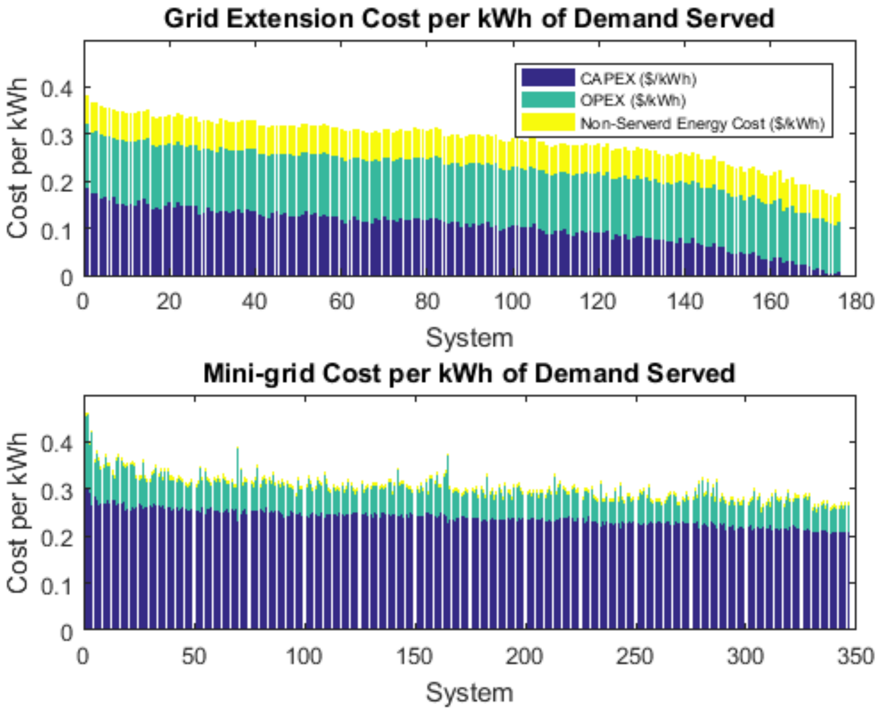

Figure 69: Total costs per demand served in different systems: investment, operation and non-served energy (high demand growth scenario).

Figure 70 presents a different cost breakdown to show the relative weight of generation, network and connection costs for different types and sizes of systems (management and non-served energy costs are not represented here).

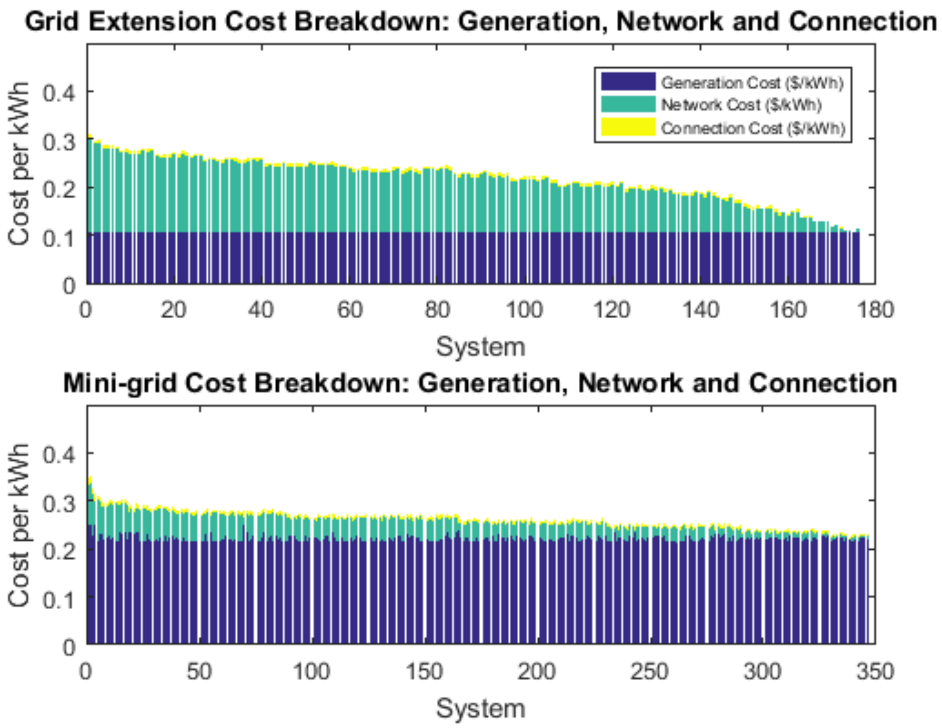

Figure 70: System cost per kWh of demand served: generation, network and connection (high demand growth scenario).

Figure 71 shows the total system cost (per kWh of demand served) for isolated systems. Since the demand is doubled, lower-income households (customer type 1) are electrified with AC systems instead of solar kits.

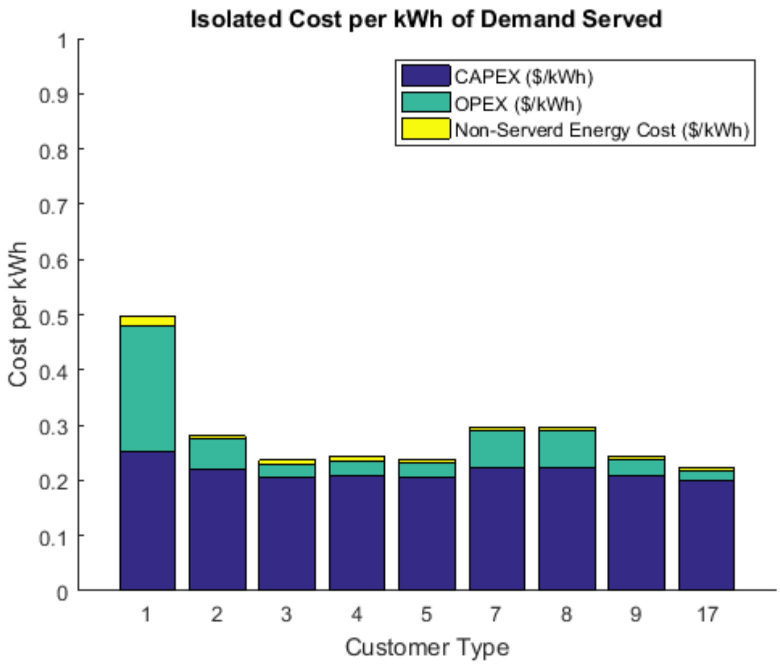

Figure 71: Cost per kWh of demand served of isolated systems (high demand growth scenario).

10.1.5. Fully Reliable Power Grid

In this case, we assume that the power grid is fully reliable so it will serve all the demand of consumer electrified with grid extensions.

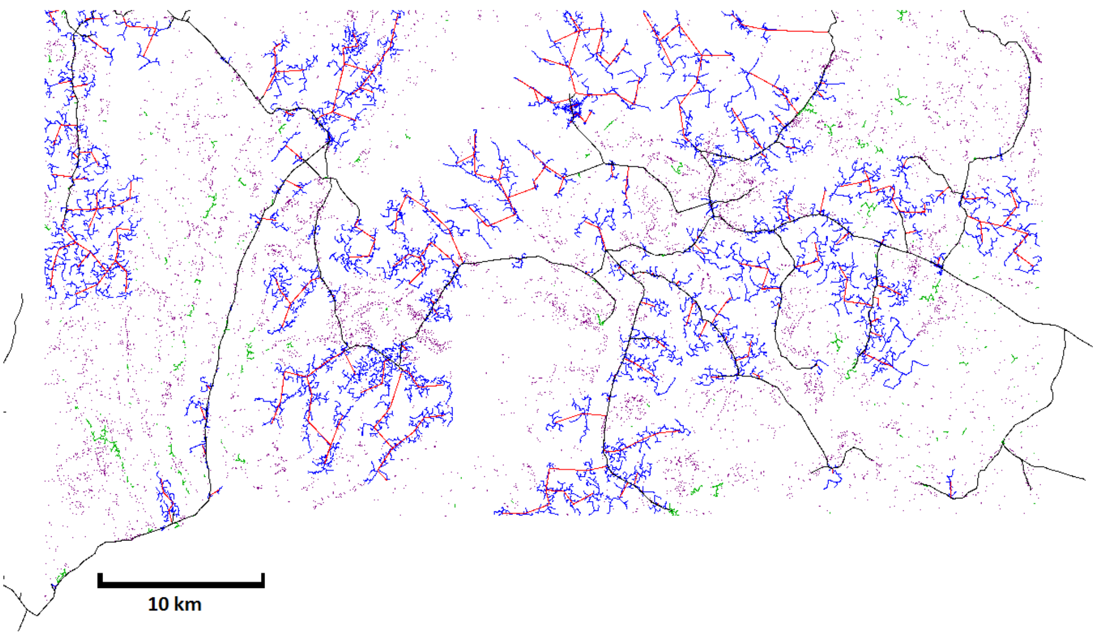

Figure 72: Fully reliable power grid scenario. The MV existing power grid is represented with black lines.

Table 13 provides a summary of the final electrification solution.

	Microgrids	Isolated	Grid Extensions	All
Number of Customers	4,061	11,566	37,082	52,709
Fraction of Customers	0.08	0.22	0.70	1.00
CAPEX Per Customer ($/yr)	189.58	170.55	108.19	128.15
OPEX Per Customer ($/yr)	54.34	48.53	141.22	114.19
Non-served Energy Cost Per Customer ($/yr)	5.19	54.44	0.00	12.35
Final Cost Per Customer ($/yr)	249.12	273.52	249.41	254.68
Total CAPEX ($/yr)	769,894	1,972,545	4,012,047	6,754,487
Total OPEX ($/yr)	220,681	561,305	5,236,606	6,018,592
Total Non-served Energy Cost ($/yr)	21,084	629,698	0	650,782
Final Cost ($/yr)	1,011,660	3,163,548	9,248,653	13,423,861
Fraction of Demand Served (p.u.)	0.986	0.900	1.000	0.984
Cost Per kWh of Demand Served ($/kWh)	0.312	0.315	0.223	0.241

Table 13: Fully reliable power grid scenario: solution summary.

Figure 73 shows the total system cost (per kWh of demand served) for grid extensions and mini-grids.

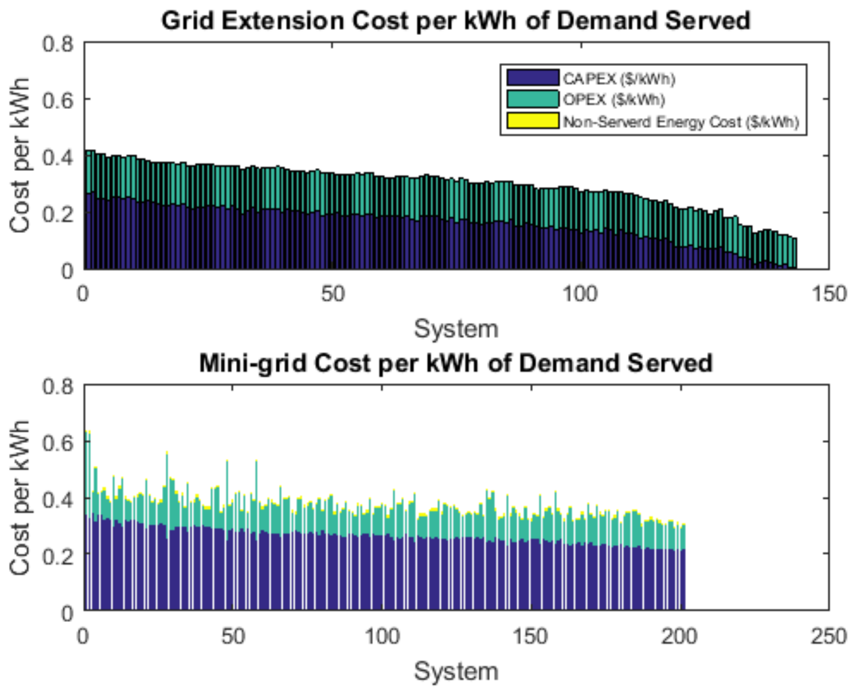

Figure 73: Total costs per demand served in different systems: investment, operation and non-served energy (fully reliable power grid scenario).

Figure 74 presents a different cost breakdown to show the relative weight of generation, network and connection costs for different types and sizes of systems (management and non-served energy costs are not represented here).

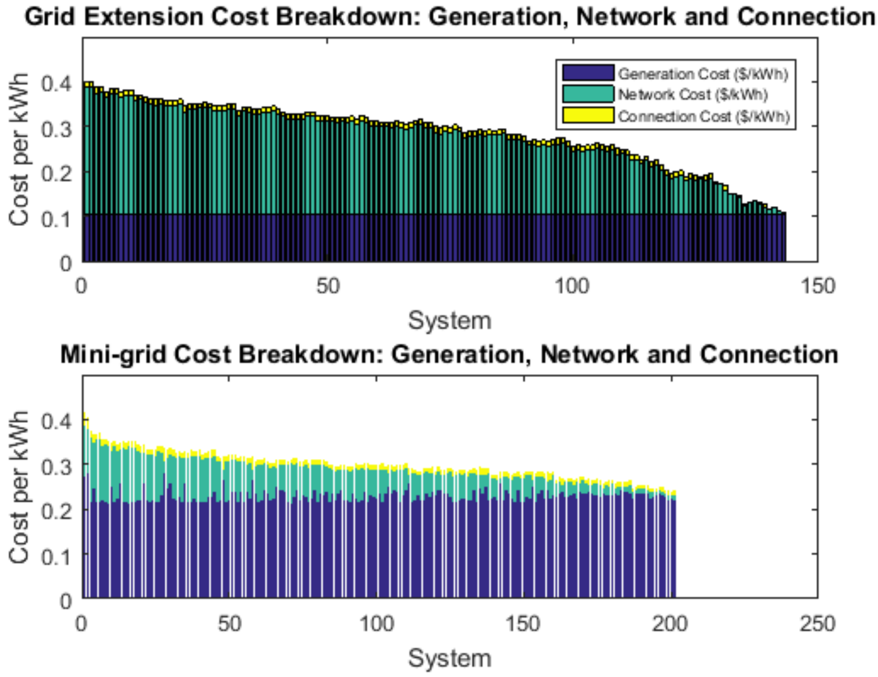

Figure 74: System cost per kWh of demand served: generation, network and connection (fully reliable power grid scenario).

Figure 75 shows the total system cost per kWh of demand served for isolated systems.

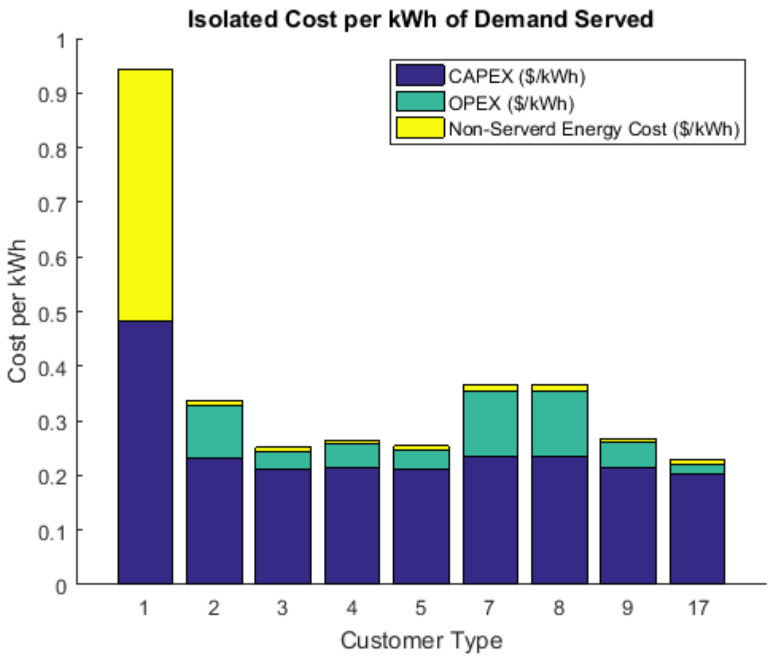

Figure 75: Cost per kWh of demand served of isolated systems (fully reliable power grid scenario).

10.2. Mini-Grid Generation Results

This section shows the generation results of two scenarios. In the first one, we assume that only renewable solutions are available. In the second one, we allow the diesel generator to serve all the demand, removing the 30% constraint imposed in the case example presented in Section 4.

For each scenario, we provide the look-up table generation and the dispatch/reliability information for 5,000 aggregated demand profiles. Although generation designs do not change in the first points of the look-up table, it is interesting to see how the solution for 5,000 aggregated demand profiles varies depending on the scenario.

10.2.1. Renewable Scenario

In this scenario, we only allow renewable technologies when calculating the generation designs. Table 14 shows the characteristics of the designs. As in the case example described in Section 4, the management costs (part of the OPEX shown in Table 14) are calculated assuming that each sample profile corresponds to a lower-income household (customer type 1). Internally, REM uses the actual number of consumers of a cluster to compute management costs, not the number of sample profiles (since a type of consumer may comprise multiple sample profiles).

Number of Sample Profiles	1	10	50	100	250	500	5,000	50,000
Peak Demand (kW)	0.08	0.78	3.86	7.71	19.28	38.55	385.50	3,854.98
Average Demand (kW)	0.03	0.30	1.50	2.99	7.47	14.95	149.48	1,494.79
Solar Capacity (kW)	0.25	2.25	11.50	23.25	57.75	115.50	1,146.75	11,738.50
Battery Capacity (kWh)	1.38	17.94	85.56	169.74	425.04	861.12	8,611.20	86,112.00
Generator Capacity (kW)	0	0	0	0	0	0	0	0
Fraction of Demand Served	0.95	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Percentage of Diesel Used (p.u.)	0	0	0	0	0	0	0	0
CAPEX per Demand Served ($/kWh)	0.29	0.22	0.21	0.20	0.20	0.20	0.20	0.20
OPEX per Demand Served ($/kWh)	0.44	0.23	0.13	0.09	0.06	0.06	0.05	0.05
Non-Served Energy Cost per Demand Served ($/kWh)	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Cost per Demand Served ($/kWh)	0.76	0.45	0.34	0.30	0.27	0.26	0.26	0.26
CAPEX ($/yr)	71	570	2,652	5,225	12,998	26,130	260,671	2,626,673
OPEX ($/yr)	110	584	1,627	2,319	4,170	7,257	62,678	618,280
Non-Served Energy Cost ($/yr)	9	14	103	200	528	868	9,497	71,778
Total Cost ($/yr)	189	1,168	4,382	7,744	17,696	34,255	332,846	3,316,731
CAPEX per Profile ($/yr)	70.75	56.99	53.05	52.25	51.99	52.26	52.13	52.53
OPEX per Profile ($/yr)	109.54	58.35	32.53	23.19	16.68	14.51	12.54	12.37
Non-Served Energy Cost per Profile ($/yr)	8.67	1.44	2.06	2.00	2.11	1.74	1.90	1.44
Total Cost per Profile ($/yr)	188.95	116.79	87.64	77.44	70.78	68.51	66.57	66.33

Table 14: Generation design samples in the look-up table (renewable scenario).

Figure 76 shows the costs of generation (CAPEX and OPEX) plus non-served energy for off-grid systems.

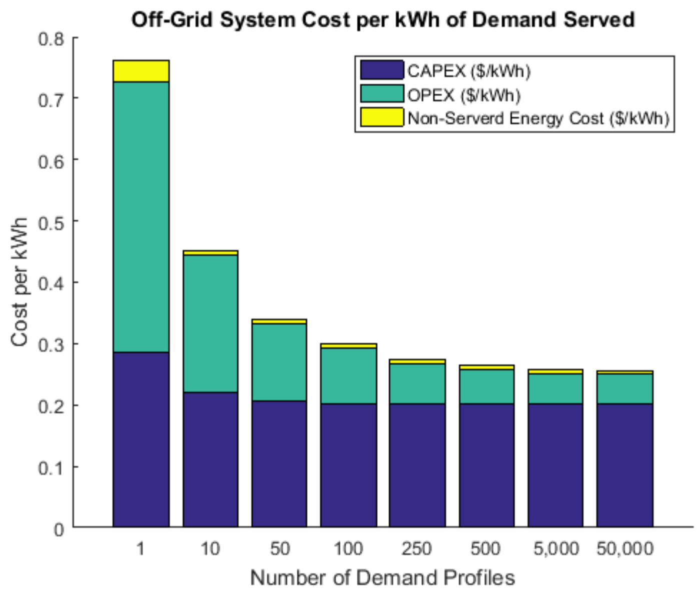

Figure 76: Off-grid system cost per kWh of demand served (renewable scenario).

Figure 77 shows the dispatch for a couple of days in a mini-grid with 5,000 demand profiles. Figures 78 shows the amount of demand served for each hour of the day.

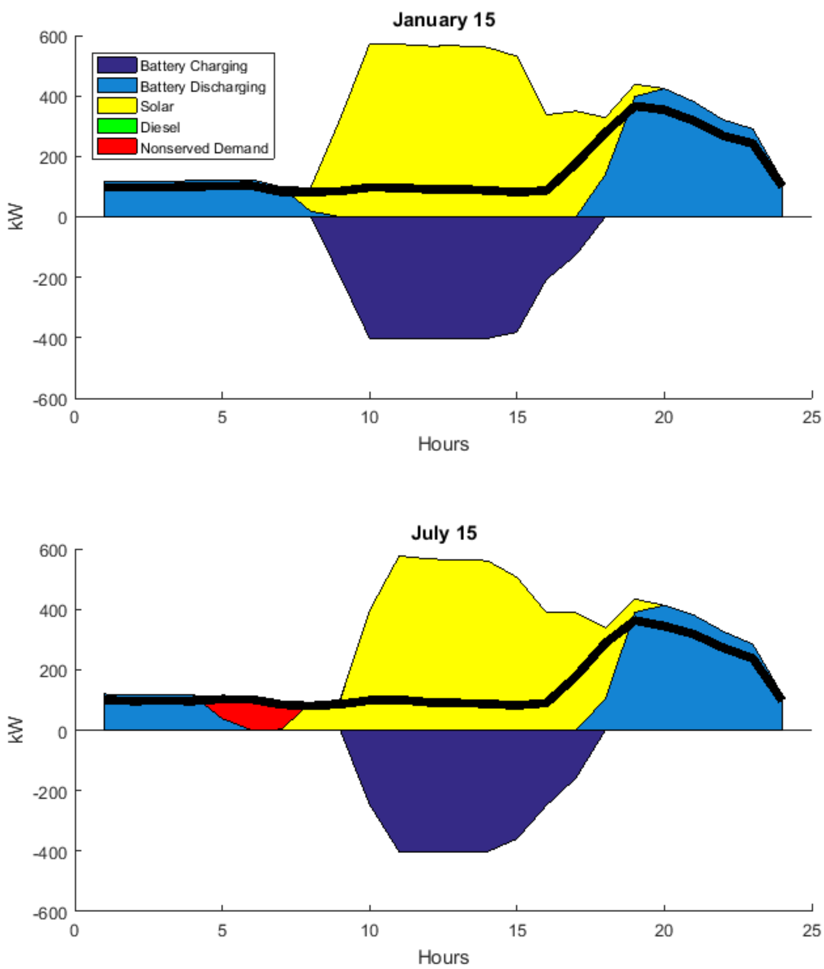

Figure 77: Daily sample dispatch with only renewable energies of a mini-grid with 5,000 demand profiles. The black line represents the total demand (critical plus non-critical).

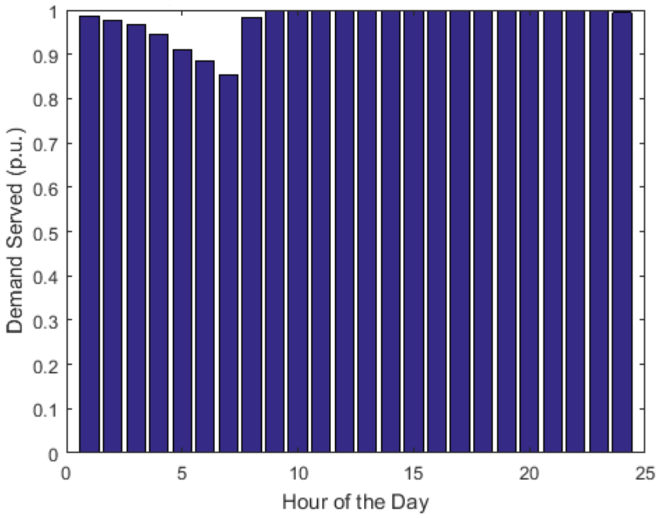

Figure 78: Demand served each hour of the day for 5,000 demand profiles (renewable scenario).

10.2.2. Unconstrained Diesel Scenario

In this scenario, we allow REM to use the diesel generator to serve all the demand when calculating the generation designs. Table 15 shows the characteristics of the designs.

Number of Sample Profiles	1	10	50	100	250	500	5,000	50,000
Peak Demand (kW)	0.08	0.78	3.86	7.71	19.28	38.55	385.50	3,854.98
Average Demand (kW)	0.03	0.30	1.50	2.99	7.47	14.95	149.48	1,494.79
Solar Capacity (kW)	0.25	2.25	11.50	23.25	57.75	115.50	312.75	3,107.25
Battery Capacity (kWh)	1.38	17.94	85.56	169.74	425.04	861.12	0.00	0.00
Generator Capacity (kW)	0	0	0	0	0	0	300	2,750
Fraction of Demand Served	0.95	0.99	0.99	0.99	0.99	0.99	0.95	0.93
Percentage of Diesel Used (p.u.)	0.00	0.00	0.00	0.00	0.00	0.00	0.74	0.71
CAPEX per Demand Served ($/kWh)	0.29	0.22	0.21	0.20	0.20	0.20	0.04	0.04
OPEX per Demand Served ($/kWh)	0.44	0.23	0.13	0.09	0.06	0.06	0.20	0.20
Non-Served Energy Cost per Demand Served ($/kWh)	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Total Cost per Demand Served ($/kWh)	0.76	0.45	0.34	0.30	0.27	0.26	0.26	0.26
CAPEX ($/yr)	71	570	2,652	5,225	12,998	26,130	48,357	461,315
OPEX ($/yr)	110	584	1,627	2,319	4,170	7,257	251,532	2,379,405
Non-Served Energy Cost ($/yr)	9	14	103	200	528	868	18,546	273,453
Total Cost ($/yr)	189	1,168	4,382	7,744	17,696	34,255	318,435	3,114,173
CAPEX per Profile ($/yr)	70.75	56.99	53.05	52.25	51.99	52.26	9.67	9.23
OPEX per Profile ($/yr)	109.54	58.35	32.53	23.19	16.68	14.51	50.31	47.59
Non-Served Energy Cost per Profile ($/yr)	8.67	1.44	2.06	2.00	2.11	1.74	3.71	5.47
Total Cost per Profile ($/yr)	188.95	116.79	87.64	77.44	70.78	68.51	63.69	62.28

Table 15: Generation design samples in the look-up table (unconstrained diesel scenario).

As in the case example described in Section 4, the management costs (part of the OPEX shown in Table 15) are calculated assuming that each sample profile corresponds to a lower-income household (customer type 1). Internally, REM uses the actual number of consumers of a cluster to compute management costs, not the number of sample profiles (since a type of consumer may comprise multiple sample profiles).

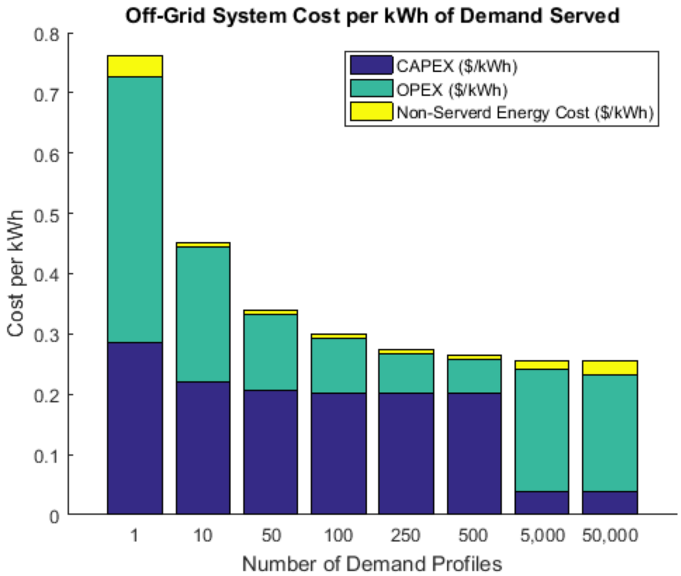

Figure 79: Off-grid system cost per kWh of demand served (unconstrained diesel scenario).

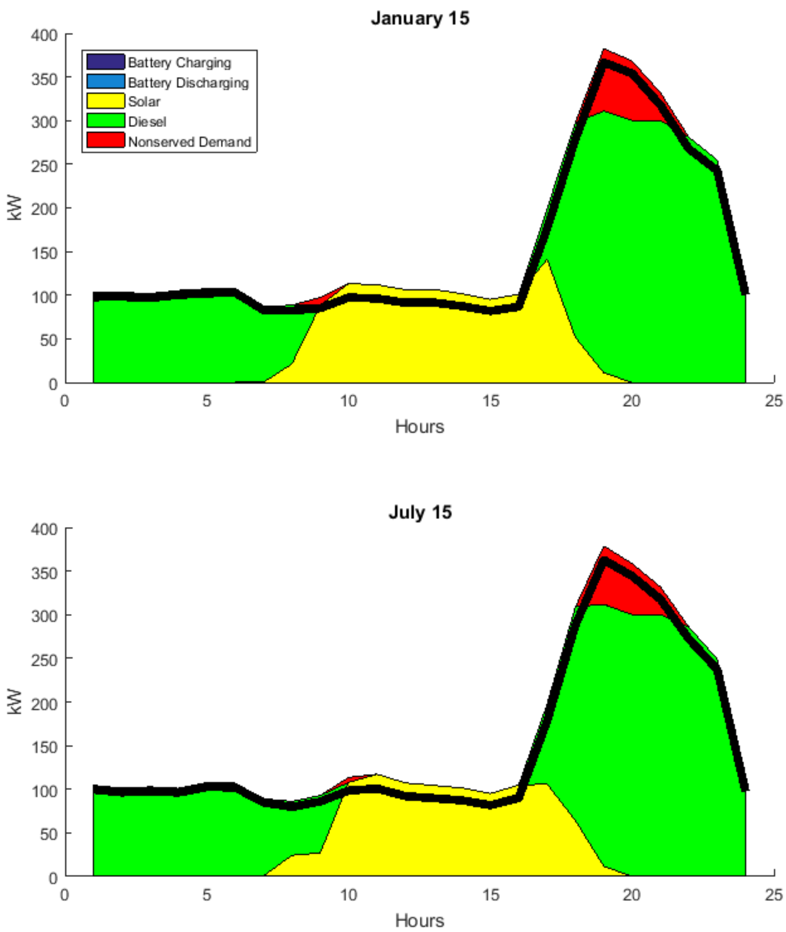

Figure 80: Daily sample dispatch with unconstrained diesel usage of a mini-grid with 5,000 demand profiles. The black line represents the total demand (critical plus non-critical).

Figure 79 shows the costs of generation (CAPEX and OPEX) plus non-served energy for off-grid systems. Figure 80 shows the dispatch for a couple of days in a mini-grid with 5,000 demand profiles. Finally, Figure 81 shows the amount of demand served for each hour of the day in the same mini-grid.

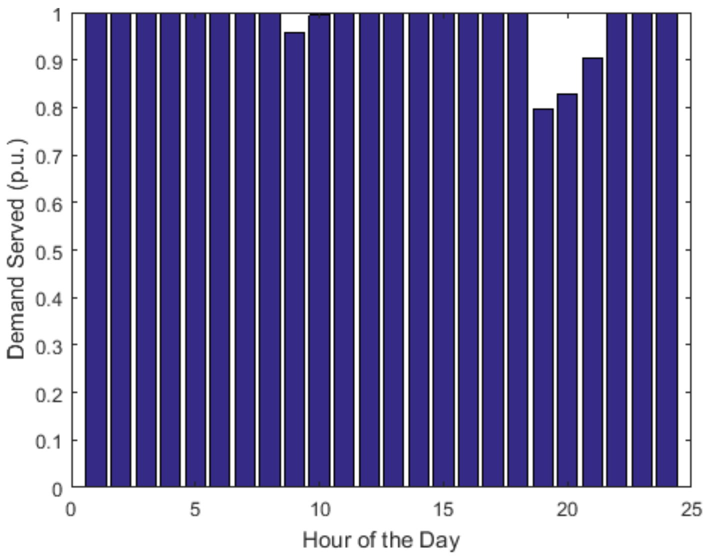

Figure 81: Demand served each hour of the day for 5,000 demand profiles (unconstrained diesel scenario).