Liberia Power Sector

Capacity Building and Energy Master Planning

Final Report, Phase 4:

National Electrification Master Plan

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Executive Summary

The primary purpose of this modeling effort has been to clarify the technical and investment needs for Liberia to achieve comprehensive electrification, assuming high penetration, cost-effectively and at a national scale. The broad conclusion is that, considering rising electricity demand due to population and economic growth over 30 years, electricity access rates of 100% in urban areas and 70% in rural areas will be most cost-effectively achieved by grid extension to reach approximately 90-95% of the targeted population, or nearly 800,000 projected households. The remaining 5-10% will be most cost-effectively served by stand-alone diesel or solar systems.

The total initial cost for this program is projected to be:

- **For grid distribution:** Approximately US$1 billion will be required for grid construction, including 9,900 km of MV distribution line, as well local LV distribution systems, transformers and all household connection costs, but omitting costs such as power generation, high-voltage transmission lines and sub-stations, meeting a total aggregate national demand of approximately 500 MW, 79% of which (395 MW) is targeted for Monrovia itself;
- **For stand-alone systems:** Approximately US$70 million will be needed for all stand-alone systems, including diesel and solar, meeting a total national aggregate demand of approximately 10-11 MW, the majority of which will be served most cost-effectively by diesel power. Furthermore, an additional expenditure of between US$10-20 million could potentially meet a 50-100% share of the "temporary" stand-alone electricity demand throughout the county, namely the need in areas that are awaiting grid connectivity.

Multiple maps and tables throughout the document illustrate the geo-spatial aspects of this electrification plan. Generally, these emphasize the importance of population density in predicting cost-effective roll-out of grid power, in particular, to higher-density counties such as Montserrado, Margibi, Bong, Nimba, Lofa and Grand Bassa. Intensification of grid systems originating at cross-border systems and substations in parts of Maryland, Grand Gedeh, Bomi, Rivercess and Grand Cape Mount will play a crucial role in national grid roll-out. Finally, the consolidation of multiple grid systems will, over the 30 year time frame, result in reduction from around 19 separate systems in the first 5 years, to 12 systems at about the 15 year mid-point, to a final 6 interconnected systems around year 30.

Uncertainty in long-term electricity demand per household complicates estimates of recurring costs; however, model results reported here project levelized costs of power (LCOE) from each system type to be:

- $0.20 - $0.21 per kWh for grid electricity
- $0.63 - $0.64 per kWh for diesel electricity
- $0.73- $0.74 per kWh for solar photovoltaic electricity

The results of this modeling effort are presented in three phases, the first representing the initial 5 years, the second covering years 5-15, and the third corresponding to years 15-30. From a planning and policy perspective, the cost and technical conclusions of the plan's first phase should be considered the most reliable. The second and third phases, being reliant upon current cost and demand figures which become inherently less reliable the further they are projected into the future, should be considered progressively more provisional and prone to revision as plans progress and new data become available.

Research activities are already underway or planned within Liberia which will offer the potential for improvements in future planning efforts, including revisions of this master plan. These include: data gathering by LISGIS for key demand points; resource mapping and system planning by RREA; surveying at IPP systems by MLME, and numerous grid extension efforts – some of which include demand surveying – by LEC. All of these new data sources, as well as updated information on geo-located demands and equipment and other costs, should be included in consideration of this plan, as well as any planning efforts that build upon it in the future.

1. Introduction: Objective and Approach

This document offers a least-cost energy plan for Liberia as a whole, predicting both the geospatial extent and lifetime costs of Liberia's grid and off-grid power systems in both urban and rural areas for the next 30 years. This report completes the final phase of the Liberia Capacity Building and Electricity Master Planning work, funded by the World Bank, and undertaken throughout 2012 and 2013 by members of the Modi Research Group, from the Department of Mechanical Engineering and the Earth Institute at Columbia University, in New York City.

The electricity access rate in Liberia is certainly among the world's lowest, with less than 1% of the population connected to grid power, leaving the vast majority reliant upon various informal systems such as household or neighborhood-scale diesel gensets for limited and basic energy services. However, at least three major electricity projects – the "cross-border" extension of power lines from neighboring countries; extension of the Cote-d'Ivoire, Sierra Leone, Liberia, Guinea (CLSG) line, as part of the West Africa Power Pool in 2014; and the progress toward various new electricity generation within Liberia, most importantly the Mount Coffee hydropower project which will restore an anticipated 50 – 80 MW of electricity generation capacity to the country – will provide power to meet a large and growing national demand, offering opportunity for transformative change in the Liberian electricity sector. These recent and anticipated developments suggest that a national electricity master plan is timely and appropriate.

This document is intended to support national electrification goals and policy, providing an estimate of costs and technical needs to achieve near universal electricity access in support of cross-sectoral and national development objectives. It should complement and support other key planning documents, such as Liberia Electricity Corporation (LEC) master plans (dated 31 March 2011 and June 2012) for the grid system serving the city of Monrovia, as well as MLME's needs assessments, and various planning efforts and projects underway with the Rural and Renewable Energy Agency (RREA). It is also intended as a guide for national planners and policymakers, as well as donor organizations, lenders and investors, for quantification and prioritization of investments to achieve time-bound electricity access targets nationwide. As a national-scale plan this analysis does not have the precision of a project design specification. It will require more detailed, ground-level surveying and engineering design for practical implementation. Its goal is to provide a realistic cost estimate and practical approach to comprehensive electrification of Liberia.

This work was supported by and enjoyed close collaboration with multiple local Liberian partner organizations:

1) the Ministry of Lands, Mines and Energy (MLME), as the lead agency, has overseen the modeling effort as a whole ensuring it proceeds in accordance with Liberia's overall electricity access goals and development objectives;

2) Liberia Electricity Corporation (LEC), the electric utility providing service to Monrovia and soon to three new grid systems in "cross-border areas," which provided many key cost and technical inputs, including electricity usage and growth estimates, billing records, planning documents, project budgets, as well as cost estimates and access plans for Monrovia in recent master plan documents;

3) the Rural and Renewable Energy Agency (RREA), provided input into modeling efforts as they relate to rural access and renewable energy use in Liberia, particularly related to demand estimates for rural households and costs for solar photovoltaic systems; and

4) the Liberia Institute of Statistics & Geo-Information Services (LISGIS), which provided geo-located census data and supported geospatial aspects of data usage.

Liberia's electrification program is assumed to take place using a least-cost combination of grid expansion and off-grid systems, such as diesel mini-grids or solar systems. The modeling work predicts that high access rates – over 90% on average nationwide – will be achieved after a time-horizon of 30 years. This report addresses the question of sequenced construction of electricity systems, or "roll-out," over time, and presents this 30-year electricity expansion program in three phases: an initial phase of 5 years, a second phase of 10 years, and a final phase of 15 years. The report presents results of modeling work, both technical and cost information, by phase, showing both new expansion undertaken in each phase and cumulative results accruing over time.

This modeling work was undertaken using the Modi Research Group's primary electricity planning tool, a web-based software platform called NetworkPlanner (networkplanner.modilabs.org). This system has been used for national and sub-national scale planning work in the past, funded by the World Bank, for countries such as Kenya[1], Senegal[2], and Indonesia (work in progress). This approach relies upon two primary classes of inputs. The first is geospatial data, of two main types, a) demands points, whether human settlements or other demands like schools and health facilities,

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[1] Parshall, L., et al. National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of Kenya. Energy Policy. http://modi.mech.columbia.edu/wp-content/uploads/2013/04/Kenya-Paper-Energy-Policy-journal-version.pdf

[2] Sanoh, A., et al. Local and national electricity planning in Senegal: Scenarios and policies. Energy for Sustainable Development, 16, pp. 13-25. http://modi.mech.columbia.edu/wp-content/uploads/2013/06/Senegal_Aly-Energy-Policy-paper-4.20.10-JEPO-S-10-00600.pdf

and b) geographically accurate information for existing and planned medium-voltage (MV) grid lines. The second class of input data is more than one hundred model settings or parameters related to a range of topics including: demographics, financial assumptions, electricity demand, technical aspects of electrical equipment, and costs – both initial and recurring – for key components of all electricity system types. For credibility and local applicability of the results, source data, model inputs, parameters and key assumptions have been cross-validated by local stakeholders throughout a series of meetings and training sessions. The key partners in this process have been the four listed previously (MLME, LEC, RREA, LISGIS).

Starting with these two classes of inputs – geospatial data and parameter values – the model performs four main steps:

First, demand is estimated for all points in the system, including both population growth and electricity demand growth, over the defined time horizon of 30 years. The key dataset in this case was the 2008 National Census, provided by LISGIS. This included geo-located census data for all populated places in the country, as well as key social service institutions such as schools and health facilities. LISGIS also provided population growth rates for urban and rural areas.

Second, the system calculates all *local* costs for electricity access and service delivery for every point in the system. In this context, "local" refers to all the equipment, replacement, operations and maintenance, and electricity tariffs within a specific location – omitting only the non-local costs, i.e. the costs of distribution line to connect separate locations with medium-voltage grid lines. Local costs for grid connection of a community include the costs of all low-voltage distribution lines, transformers, and household connection costs, such as meters and service drops, as well as all electricity tariffs summed over the entire time horizon. By definition, all diesel mini-grid or solar PV electricity supply in a community include only local equipment and costs, since these systems, in this model framework, are "standalone" and do not inter-connect separate communities.

Third, the model compares only the local costs of connecting a community to the grid with the local costs of the least expensive off-grid option. The software then uses the difference between the local grid cost and local "standalone" system costs as an opportunity cost of connecting that point to its nearest neighbor.

Fourth and finally, the system uses the geographic distances between all points in the system, along with this comparison of local grid and off-grid costs for each point, to determine which locations in a least-cost system should be connected with the electricity grid, and which should instead utilize the lowest-cost off-grid system. It then algorithmically constructs the grid that connects these points in the most efficient manner.

The electricity plan is presented in 4 additional sections of this report: Section 2, “Geospatial Data Inputs” briefly discusses the key characteristics of the geospatial census data and existing medium-voltage grid lines. Section 3, “Parameters and other Quantitative Inputs” describes the key parameter inputs required for this modeling work, providing added detail for those, such as household demand, that are most critical for the model results. Section 4, “Model Results,” lays out in maps, tables and charts, the conclusions of this modeling effort, including the phased roll-out, in five year, ten year and fifteen year phases. Finally, Section 5, “Conclusions,” summarizes some of the key findings as well as implications for modeling and planning.

2. Geospatial Data Inputs

The following section discusses the two broad classes of *geospatial* model inputs: demand points and existing and planned medium-voltage electricity distribution lines.

2.1. Settlements and Other Demand Points: Liberia 2008 Census Data

A great benefit to this modeling effort in Liberia has been the excellent geo-located demand data, collected by LISGIS, the national statistics agency, as part of the 2008 census. This dataset covers all populated places in the country, nearly 14,000 points in all, from the smallest villages (some with zero population) to the largest cities, including the capital, Monrovia, with a population of roughly 1 million. The population data includes identifying information for various administrative levels, such as counties, districts, and clans. More important for this modeling effort, each settlement is geo-located, as a point possessing a single latitude / longitude pair. The census data also include points representing primary and secondary schools, as well as various health facilities, including clinics, health centers and hospitals. Because the schools were very numerous, their points were merged to the nearest settlement using a spatial join. Each facility is assigned to the nearest settlement, and the electricity demand for each education facility was added to the residential demand for the settlement. Largely to preserve electrification information for hospitals, all health facilities were preserved as independent points. Together, these geo-located points – residences with schools and health points -- became the basic demand point input for the electricity modeling effort.

Table 1: Settlements (Number and Percent) for Different Population Ranges (Liberia, 2008 Census data)

Population Range	**Settlements grouped by population range**		**CUMULATIVE**	
	# settlements	**% of settlements**	**# settlements**	**%**
0	44	0.3%	44	0.03%
1-10	1,413	10.15%	1,457	10.5%
11-25	2,629	18.9%	4,086	29.3%
26-50	2,672	19.2%	6,758	48.6%
51-100	2,319	16.7%	9,077	65.2%
101-250	2,304	16.5%	11,381	81.8%
251-500	1,475	10.6%	12,856	92.3%
501-1K	867	6.2%	13,723	98.6%
1K-5K	176	1.3%	13,899	99.8%
5K-10K	7	0.05%	13,906	99.9%
10K-25K	8	0.06%	13,914	99.95%
25K-50K	4	0.03%	13,918	99.98%
50K-100K	2	0.01%	13,920	99.99%
100K-250K	0	0%	13,920	99.99%
250K-500K	0	0%	13,920	99.99%
500K-1M	1	0.01%	13,921	100%
Total	**13,921**	**100%**		

A key characteristic of the Liberian population distribution, as shown in Table 1 above is that, apart from Monrovia, the population is overwhelmingly rural, residing in thousands of very small villages and few medium sized towns. As this table shows, nearly 30% of all settlements in the country have fewer than 25 people. Small villages with fewer than 100 people comprise 65% of settlements; 80% have fewer than 250 people (villages); 98% have less than 1,000 residents; and nearly 99.9% have fewer than 5,000. Only 21 settlements have between 5,000 and 100,000; and only one, Monrovia, is greater than 100,000, at approximately 1 million.

Table 2 below shows summary metrics derived from Liberia's 2008 census data, aggregated at the level of the country's 136 districts. Because of the prevalence of small settlements, the national mean population density of 129 persons per square kilometer is much closer to the minimum of 6 persons per km^2 than to the maximum of 4,511 persons per square kilometer, which applies to Montserrado County, specifically Monrovia. Both the mean national population density and the mean national household density values fall at lower end of the top quintile, meaning that around 80% of districts have lower densities. To summarize, the population is very sparse: 80% of all districts have fewer than 130 persons / km^2 and fewer than 30 households / km^2.

Table 2: Population and Household density figures for Liberia's districts, separated into quintiles.

	Area	Population & Density		Households & Density	
	km^2	Persons	Persons / km^2	Households	Households / km^2
Total	36,987	3,476,608		733,906	
Mean	272	25,563	129	5,396	45
Min	8	643	6	112	1
Max	1,207	970,824	4,511	200,934	2,659
Quintile 1	8 – 99	643 - 4,868	6 – 26	112 - 765	1 - 5
Quintile 2	100 - 149	4,869 - 10,057	27 – 49	766 – 1,554	6 - 9
Quintile 3	150 - 240	10,058 - 17,137	50 – 80	1,555 - 2,975	10 - 16
Quintile 4	241 - 399	17,138 - 30,330	81 – 128	2,976 - 6,479	17 - 30
Quintile 5	400 - 1,207	30,331 - 970,824	129 - 4,511	6,480 - 200,934	31 - 2,659

Data was sought for multiple other classes of demand points, but generally these were not included in the modeling effort for reasons specific to each type:

Productive demands (particularly sites for resource extraction such as mining, forestry, rubber plantations, as well as industrial production): Productive uses are important for an overall understanding of Liberia's energy demands, and many of the locations for these demands are known. However, incorporating them into a long-range electricity planning effort such as this was difficult, primarily because it was not clear which sites would most likely rely on power from the national or regional electricity grid versus power from dedicated systems on-site. Information was sought from local sources regarding plans for electricity for mining, in particular, but was not available at the time. In absence of this information, model runs were made including productive demands. These high-demand points, quite predictably, overwhelmed all other electricity demands, particularly in the short term, yielding the obvious conclusion that if sufficient grid power is available for mining and other productive sites, and is priced below rates that can be produced on-site (particularly using diesel gensets), then it is certainly viable to connect them to the grid. This conclusion may be helpful in general, but is not particularly useful as a part of a detailed, geo-spatial assessment such as this. Plans and designs for site-specific electricity supply for high-demand productive sites have thus been omitted from this report.

Markets: Markets and commercial centers are numerous and highly distributed, and meeting their electricity demand is important for economic growth and other development objectives. However, LISGIS recommended against using existing market location data due to concerns with age and accuracy, so this point type was omitted. The absence of demand for markets, and the commercial sector generally, is an important limitation for this modeling effort. However, it is encouraging for future modeling work that LISGIS reports that it is planning surveying to address this crucial data gap.

Other non-residential demands: Geo-spatial data for the non-residential demands such as street-lighting, government offices and police stations, and border crossings were not available at the time of this modeling, but data collection efforts are underway by LISGIS. Estimates of these demands were far below 1% of the total electricity demand, when compared to residential demand, including population and demand growth.

2.2. Existing and Planned Medium-Voltage (MV) Grid Lines

The Earth Institute team developed a geospatial file representing the existing grid systems for Liberia, as well as those planned for the near term, within the next three years. This file has three main component sources:

(1) **Monrovia Grid:** Grid electricity service is currently only available from LEC within Monrovia, and even here it serves less than one percent of the city's population. Figure 1 below shows the extent of grid within the city, from an LEC-provided CAD plan dated 2012. This grid system was incorporated into geo-spatial modeling as existing grid.

Figure 1: Existing medium-voltage line within greater Monrovia (LEC, 2012).

(2) **Cross-border systems:** A representation of the cross border MV systems was derived from a Government of Norway, World Bank, USAID & JICA funded study[3] and brochures provided by LEC. These maps were digitized by Earth Institute staff in New York using existing roads as indications of pathways for grid lines. The three cross border systems are identified by the biggest settlement served in each system as (i) Yekepa, (ii) Zwedru and (iii) Harper, respectively, from North to South.

(3) **CLSG sub-stations**: Coordinates for the CLSG substations were obtained from a Korean Electric Power Corporation (KEPCO) consultant report.[4] The substations alone and not the entire path of the high voltage CLSG line were considered in our model to be starting locations for medium voltage extensions. These substations have yet to be constructed, with a commissioning date expected in Q2 2016. Any customers served by the WAPP system are constrained to originate from one of the four substations of (i) Mano, (ii) Buchanan, (iii) Yekepa, or (iv) Monrovia.

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[3] World Bank. *Scope and Rough Cost Estimate for Recovering Pre-War T&D System Capacity*. May 2012

[4] Korea Electric Power Corporation (KEPCO). *Final Line Route Study Report*. January 2010. (pg. 89-95)

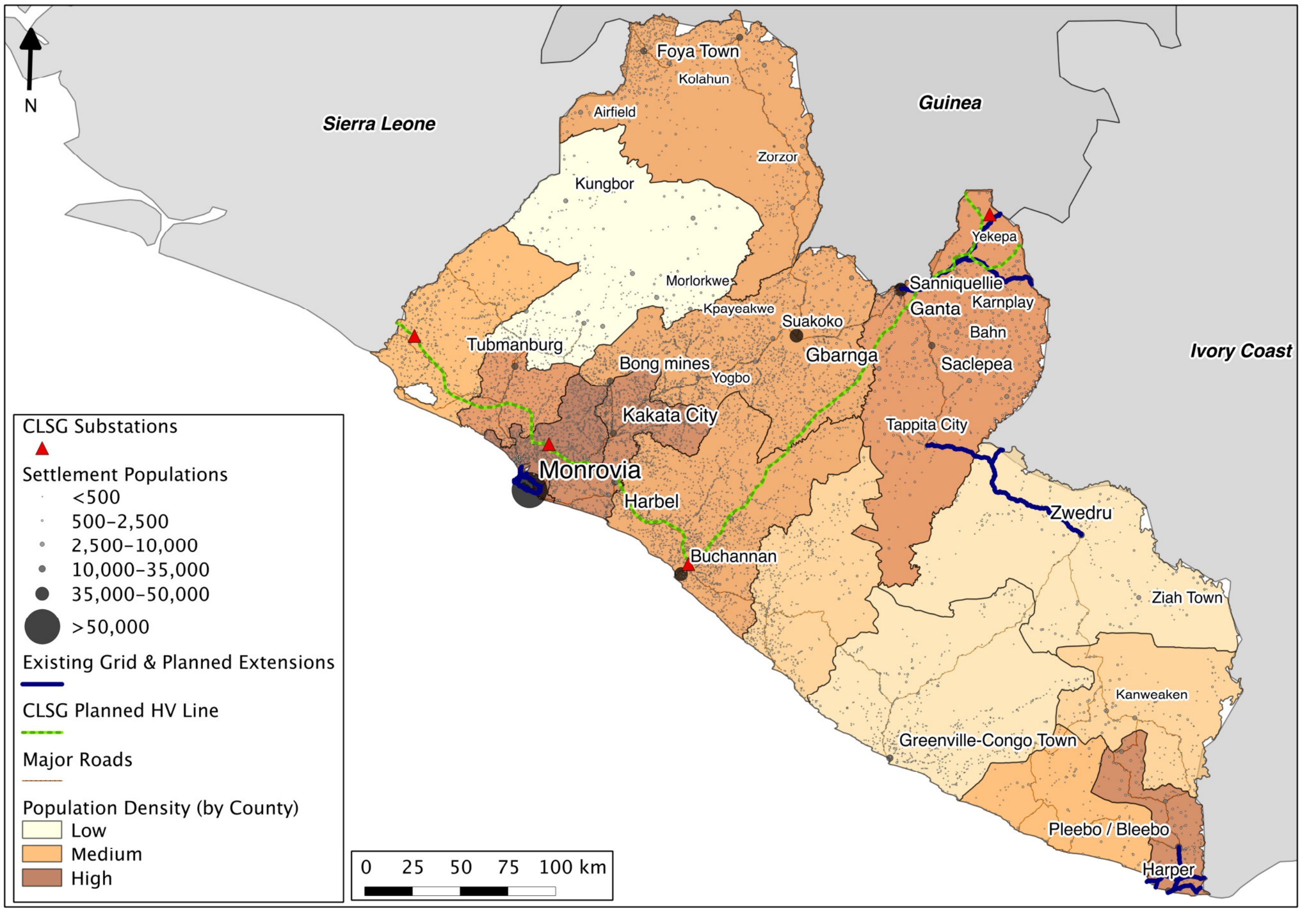

Figure 2: Map of populated places with existing and planned electricity grid, with districts shaded according to population density.

Figure 2 above illustrates the existing and planned grid lines, as well as settlements. The CLSG (WAPP) line, in light green, extends through the center of the country along a pre-existing railway line, and the cross-border lines, in dark blue, extend from neighboring countries into Liberia. Note that Monrovia's circle is not drawn to scale; to do so would make it difficult to visualize all other settlement points in a manner that showed any variation in size. It is clear that the overwhelming percentage of settlements are very small, essentially points on this map. The other most important settlements, often county capitals, are typically less than 25,000 in population, with only a few ranging from 25,000 to 100,000, and none above this range, except Monrovia. It is also important to note that the larger settlements tend to fall in three locations: on the coast, near the national border, or in a relatively high population "corridor" extending from Monrovia to the north-east through Gbarnga and toward Ganta and Sanniquellie.

Given this population distribution, it is clear why the focus on electrification is centered on Monrovia: reaching customers there will serve roughly one-third of the national population more quickly and at relatively low cost per household. Furthermore, electricity supply is able to take advantage of various economies of scale, given the high-density of customers and higher typical incomes and electricity demand of urban residents.

However, addressing high electricity access as a national objective requires consideration of the other two-thirds of Liberians. To reach high penetration rates outside of Monrovia, these much smaller but still significant towns and small cities, ranging from about 5,000 to 60,000 in population, are key targets for electrification. Some are included in the cross-border electrification effort that connects Liberian towns to electricity systems in neighboring countries, or may be connected via sub-stations along the Côte d'Ivoire-Liberia-Sierra Leone-Guinea line. A final category must be electrified from domestic sources; the approach taken here will include these sites as municipal mini-grids which expand over time to connect with the main national grid. This approach is described in the model results section which details sequenced roll-out of grid and off-grid power systems.

3. Parameters and Other Quantitative Inputs

The geo-spatial dataset described in the previous section is combined, in the model software, with numerous demographic, financial, technical, cost and other parameters. The complete list of parameters is provided in Appendix B to this report. The following section focuses on those inputs that are the most deterministic of the overall model outcome.

3.1. Residential demand estimates and related growth

A sound estimate of household electricity demand is essential for understanding current consumption and as a basis of projection into the future. In Liberia, both the current consumption and predicted future growth are difficult to establish accurately for several reasons, most of which stem from the post-conflict conditions under which electricity access is being rapidly re-established. While LEC works to revitalize a largely destroyed national utility, a range of informal energy services have proliferated. These include small, private diesel gensets operating at a neighborhood scale which currently serve an unknown (but likely quite large) number of households, shops and other small consumers nationwide. Smaller scale household systems are also common, though there is a scarcity of information regarding these systems and consumption patterns.

The following section reviews key data sources and assumptions used for estimating household electricity demand. Ultimately this model assumes a range of household electricity demand, from a low of 300 kWh/year per household in the smallest communities, rising to 2,400 kWh/year for households in Monrovia, the largest urban center.

3.1.1. Demand in urban households: LEC Data for Monrovia

LEC currently provides fewer than 5,000 residential customers in Monrovia with grid electricity powered by diesel gensets. Many LEC customers are in the most commercially developed, affluent areas of the nation's wealthiest city. Thus, several factors complicate the use of LEC billing and consumption records a basis for estimating national household demand:

- **Limited Customer Information:** LEC's set of residential customers is small (6,200 accounts in 2012[5]), and is likely to be a non-representative subset of urban households, with

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[5] Liberia Electricity Corporation. *Electric Master Plan.* March 2011 (pg. 17)

higher incomes than rural areas, and thus high-consumers. In addition, LEC staff report that many current utility customers provide informal connections to others nearby. Furthermore, most customers have been served for less than five years, making consumption trends difficult to ascertain.

- **High Tariffs:** LEC charges tariffs in excess of US$0.50 per kWh[6] to recover costs of high-cost diesel generation.
- **Latent Demand:** LEC master plans for Monrovia[7] emphasize the difficulty in demand forecasting given that "latent" demand for currently unconnected customers is far larger than growth among the few who are currently connected.

These factors may have contrary or varying effects both on household demand overall, and among subsets of consumers with different price sensitivities. Some factors, such as the skew of the current LEC service toward more affluent households, suggest that LEC's average consumption values are higher than they would be in a future system with greater penetration in Monrovia and beyond. Other factors, like the high LEC tariffs, likely depress current consumption relative to future values as tariffs will eventually come to reflect a lower-cost generation mix from sources such as hydropower and imported electricity. Nonetheless, current LEC figures are a rare source of data for actual consumption in Liberia, and should be considered – with careful interpretation – for insight into latent demand among unconnected households in Monrovia.

Table 3 below shows consumption data for LEC's residential customers divided in five consumer classes.[8] Due to the extremely high consumption values of the "upper" and "high" income consumer classes, as well as the factors listed above skewing data toward high consumers, a weighted average of all five consumer classes was considered unrealistically high as a guide for city-wide household consumption. Instead, the "low income" consumer class, which is the largest proportionally of the five, was considered most representative, and the center of this consumption range – 200 kWh per month, or 2,400 kWh per year – was chosen as an average *for all households in Monrovia*.

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[6] At the time of this modeling work, the LEC tariff was US$0.54 per kilo-watt-hour.

[7] Liberia Electricity Corporation, June, 2012. Electric Master Plan

[8] Findings based on tabular data provided by the Corporate Planning Department of the Liberia Electricity Corporation. *Demand Forecast Revised Mar. 7 2011*.

Table 3: Residential consumption data (LEC Planning Department)

	Consumption Classes (defined by LEC)				
	Poor	Low Income	Middle Income	Upper Income	High Income
Consumption [kWh/month]	<100	100 - 300	300 – 600	600 – 1,200	>1,200
Share of 1,000 Residential Customers	260	350	206	130	54
Actual Average Consumption, kWh/yr	600	2,280	5,172	9,768	25,188

At current LEC tariffs, this implies that “low income” households in Monrovia spend more than $100 per month on electricity (while “poor” households spend perhaps $25 per month). While this is indeed a high monthly expenditure for households in a low-income country, it is not far from the prices charged by operators of neighborhood diesel gensets – referred to locally as “IPPs” – in Monrovia. These providers routinely charge flat rates of ~US$50 per month for a 1A connection for service that is both less reliable and much more limited (nighttime hours only).[9] In short, though data is limited, investigations of IPPs and LEC data both suggest that a reasonable level of consumption for households in Monrovia is likely to fall somewhere around 0.5 kWh per day, which is consistent with use of electricity for lighting, television and some higher-wattage uses, such as air conditioning or refrigeration. While costs for this consumption are currently quite high – whether through an LEC connection or local genset (“IPP”) – the generation mix of Monrovia’s supply is likely to begin shifting rapidly within the next 3-5 years[10] such that tariffs would decrease by perhaps 50% or more. Given that the projections made here apply to a 30 year time-horizon, this assumption is seen as plausible.

3.1.2. Demand in rural households: Workshop Estimate

During a training workshop in April 2013 planning representatives from LEC, RREA, MLME and LISGIS discussed electricity consumption of newly-connected households in rural Liberia. Led by

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[9] Preliminary data from pilot surveys of private genset (“IPP”) operators in Monrovia, August 2012, in collaboration with MLME researchers found that these rates were standard, and equated to approximately US$1-2 per kWh.

[10] Mt. Coffee hydro has a targeted in-service data of late 2015/early 2016. LEC Master Plan, June 2012.

RREA staff, the group estimated a value of approximately 380 kWh per year as outlined in Table 4 below.

Table 4: RREA/EI: Estimate of Baseline Electricity Consumption by a Typical Rural Customer (Source: Data Analysis Workshop, Monrovia, April 2013: with participants from LEC, RREA, MLME, and LISGIS)

Appliance	units [quantity]	Power Consumed [W]	Hours of use per day [hrs]	Daily Energy Use [Wh/day]	Annual Energy Use [kWh/yr]
Lighting (CFL bulbs)	5	15	5	375	137
Radio	1	25	12	300	110
Portable DVD	1	25	4	100	37
TV	1	65	4	260	95
Phone Charger	1	1	4	4	1
			TOTAL	1039	379

Based on these discussions with RREA and additional discussions with LEC planning staff, the value for household consumption in the smallest households – those with 100 persons or fewer – was set at 25 kWh per month, or 300 kWh per year.

3.1.3. Variation in Household Demand with Community Size

The NetworkPlanner software enables modeling of the variation in household electricity demand with the size of the settlement in which a household is located. This is to reflect the tendency for urban households to use more electricity than those in smaller settlements.[11] The manner in which this variation in household demand was modeled in this effort is illustrated in Figure 3 below.

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[11] Othman, Nor Salwatibt. (February 2011). Assessing the Elasticities of Electricity Consumption for Rural and Urban Areas in Malaysia: A Non-linear Approach, *International Journal of Economics and Finance*. www.ccsenet.org/ijef.

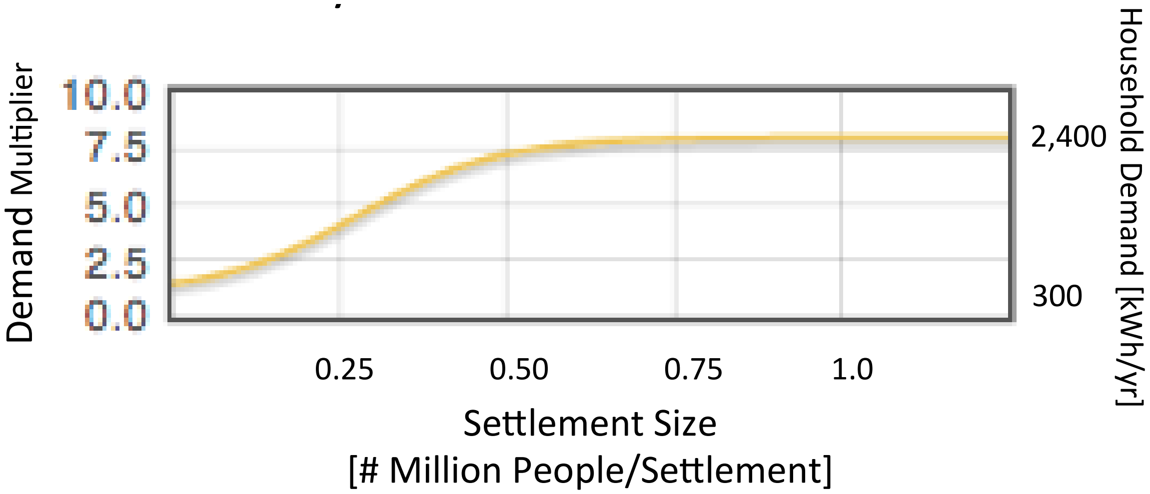

Figure 3: Modeling Demand as a function of Settlement Size

The curve is logistic, showing a multiplier on the left y-axis which is applied to the base figure of 300 kWh per year as settlement size grows, yielding household demands ranging from 300 – 2,400 kWh/yr, shown on the right y-axis. The unusual settlement pattern in Liberia, discussed in prior sections, means that the important portions of the curve for modeling purposes are at the low and high extremes – near the start of the curve, below 0.100 (100,000 population) and around 1 million. The base value of 300 kWh/yr (a multiplier of 1) is set for households in small villages of 100 persons or fewer; this rises to 600 kWh/yr (a multiplier of 3) for towns of 5,000; then increases to 1,200 kWh/yr in small cities of 100,000 (a multiplier of 6); and finally reaches 2,400 kWh/yr (a multiplier of 8) for Monrovia, the only settlement of 1 million. As will be shown in the following section, this curve falls within an electricity consumption range consistent with international examples.

3.1.4. Comparison of Liberia's Household Demand with Other Nations

Comparison of residential electricity use in Liberia with other developing countries can help validate the estimates provided previously. While Liberia is a low-income country, it is also resource-rich, and is expected to see substantial investment and aid inflows as it continues to rebound from past conflicts. Table 5 presents household electricity demand values from countries – both immediate neighbors and more distant countries in Africa and Asia – some of which share many factors present in Liberia, while others differ markedly in their development trajectories. Note that these values are estimates, derived from multiple sources. Figures have been rounded, and are approximate.

Table 5: Household Electricity Consumption Estimates for Various Developing Countries (multiple sources, including World Bank (http://data.worldbank.org/), and others listed in footnotes)

County	Residential Electricity Consumption [kWh per Household / Year]	Year
Benin[12]	900	2005
Ghana[13]	950	2009
Côte d'Ivoire[14]	800	2005
India[15]	1,100	2011
Indonesia[16]	1,500	2011
China[17]	950	2010
South Africa[18]	1,600	2005

As a regional neighbor with grid access rates around 70%[19] and a goal of universal access by 2020, Ghana represents a potential model for Liberia's electrification goals. Ghana itself has an average household consumption value of approximately 950 kWh/yr. Similarly, South Africa aggressively expanded electricity access to achieve rates of 75% by 2009. A 2005 study of 120 households in two recently electrified rural villages in South Africa revealed that electricity consumption is below 600 kwh/year for the majority of low-income households[20] and previous research established a value of about 1,600 kWh/year for households on average. China, with rapid rates of industrialization and urbanization, saw residential energy use rise faster than all other energy over the last 20 years, driven in part by the enormous increase in household appliance ownership. One study showed

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[12] Badarou R.M., Herbert Kouletio E. C. (2009) *Energy systems: Vulnerability – Adaptation – Resilience (VAR) 2009 Regional focus: sub-Saharan Africa-Benin. HELIO International, pages 13,19.*

[13] World Bank for percent access; Strategic Planning and Policy Division (2011), *Draft Report On Survey and Analysis of Energy use in the Residential, Industrial, Commercial and Services Sectors of the Economy, Page 22 for household size.*

[14] World Bank for percent access; for household size (Cisse A. (2011) *Analysis of Health Care Utilization in Côte d'Ivoire* Page 15); http://www.nationmaster.com/graph/ene_ele_con_by_hou_percap-electricity-consumption-households-per-capita for residential consumption.

[15] World Bank for household size, population and percent access; *Documentation of Data and Methodology Background Paper India: Strategies for Low Carbon Growth: Table 4, 37 and Annex 8: Total Power Consumed by Appliances for household electricity use.*

[16] Corporate Secretary, PT PLN (Persero) [Indonesia Electric Utility] (2011), *PLN STATISTICS 2011: table 8 ISSN: 0852-8179.*

[17] World Bank for percent access and electricity consumption per capita; Zhao X., Li N., Ma C. (2011) *Residential Energy Consumption in Urban China: Figure1,* Working Paper 1124, School of Agricultural and Resource Economics, The University of Western Australia, for percent residential electricity use.

[18] Borchers, M., et al, 2001. National Electrification Programme evaluation: Summary report. Evaluation commissioned by the Department of Minerals & Energy and the Development Bank of Southern Africa. Cape Town, Energy & Development Research Centre, University of Cape Town.

[19] World Bank, 2012. Lighting Africa Ghana Policy Report Note.

[20] Prasad, G., 2006. Social issues. In: Winkler, H. (Ed.), Energy Policies for Sustainable Development in South Africa: Options for the Future, first ed. Energy Research Centre, Cape Town (Chapter 5)

consumption in urban households across five Chinese cities range from about 1,050 - 2,100 kWh/yr.[21]

All of these values are is consistent with the assumed range for Liberian households used for this modeling effort, from a rural minimum of 300 kWh/year to an urban maximum of 2,400 kWh/year. The upper limit on the Liberia estimate used here does appear high relative to the international values; however, it is a) assigned only to households within the largest urban center (Monrovia) whereas the international examples are national averages, and b) this urban value is supported by data that obtained directly from the utility (LEC) and moreover corresponds to one of the low-consuming class of current customers.

In addition to household demand levels, household access rates are also an essential consideration in estimating aggregate demand. While a variety of targets have been discussed with energy practitioners in Liberia, perhaps the most important electricity access objectives for this analysis are those contained in LEC master plans, which include the goal of reaching 30% access by 2015 (though LEC itself acknowledges that a rate of around 15% is more likely), and the goal of achieving 70% access by 2030. Given that this higher target is set for less than 20 years from now, it seems reasonable to expect a target of near 100% in 30 years (an additional 30% in nearly double the timeframe).

Using this Monrovia value as a guide, and in discussion with local energy practitioners, target rates of 100% for urban areas, and 70% for rural areas, were chosen as the model settings for this project. Note that this defines access as any electricity service that meets the household demand – including either grid or off-grid technologies. Given the high, and in some cases quite rapid, electricity access achievements in countries such as Ghana and South Africa, as well as the high access targets LEC has set for Monrovia (which accounts for at least one-third of national demand), these targets seem reasonable.

3.1.5. Growth in Household Electricity Demand

Having established a range estimate for urban and rural household electricity demand, it is of equal importance to estimate figures for projecting demand growth into the future. Residential demand growth will have two key drivers: population growth and rising consumption per household due to

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[21] Lin, Jiang. (2004). A Tale of Five Cities: The China Residential Energy Consumption Survey, *American Council for An Energy-Efficient Economy.* *h*ttp://eaei.lbl.gov/publications/tale-five-cities-china-residential-energy-consumption-survey

economic growth. The first of these is straightforward, since the 2008 Liberian national census Increasing demand due to economic growth is inherently more difficult to predict, particularly over multiple decades, as economic growth itself can vary highly over the span of a few years, even as the generation mix in Liberia changes and unit costs fall. Anecdotally, local practitioners expect economic growth may equal 5-10% for over the short term, as resource extraction and other projects ramp up quickly. However, this rate is difficult to maintain over the long term, and will certainly be variable. After discussion with local practitioners an annual demand growth rate of 2.34% was chosen, largely because this value is consistent with the assumption that household demand will at least double over the 30 year time horizon. The comparison of current (and almost entirely latent) demand that is assumed to exist, versus projected demand that is anticipated after a tripling of demand after 30 years, is presented in Table 6 below.

Table 6: Current and Projected Household Demand.

	Current demand (largely latent)	30 year projection (with demand growth)
Model Inputs	[kWh/year]	[kWh/year]
Rural Minimum (settlements of <100)	300	600
Urban Maximum (1M, Monrovia)	2,400	4,800
Model Results		
National Average	1,100	2,100
Rural Average	480	650
Urban Average	1,800	2,650

The household demand for 20 similar income countries was assessed and results depicted in Figure 4 below, including a trend line illustrating a rise in electricity consumption as GDP increases.

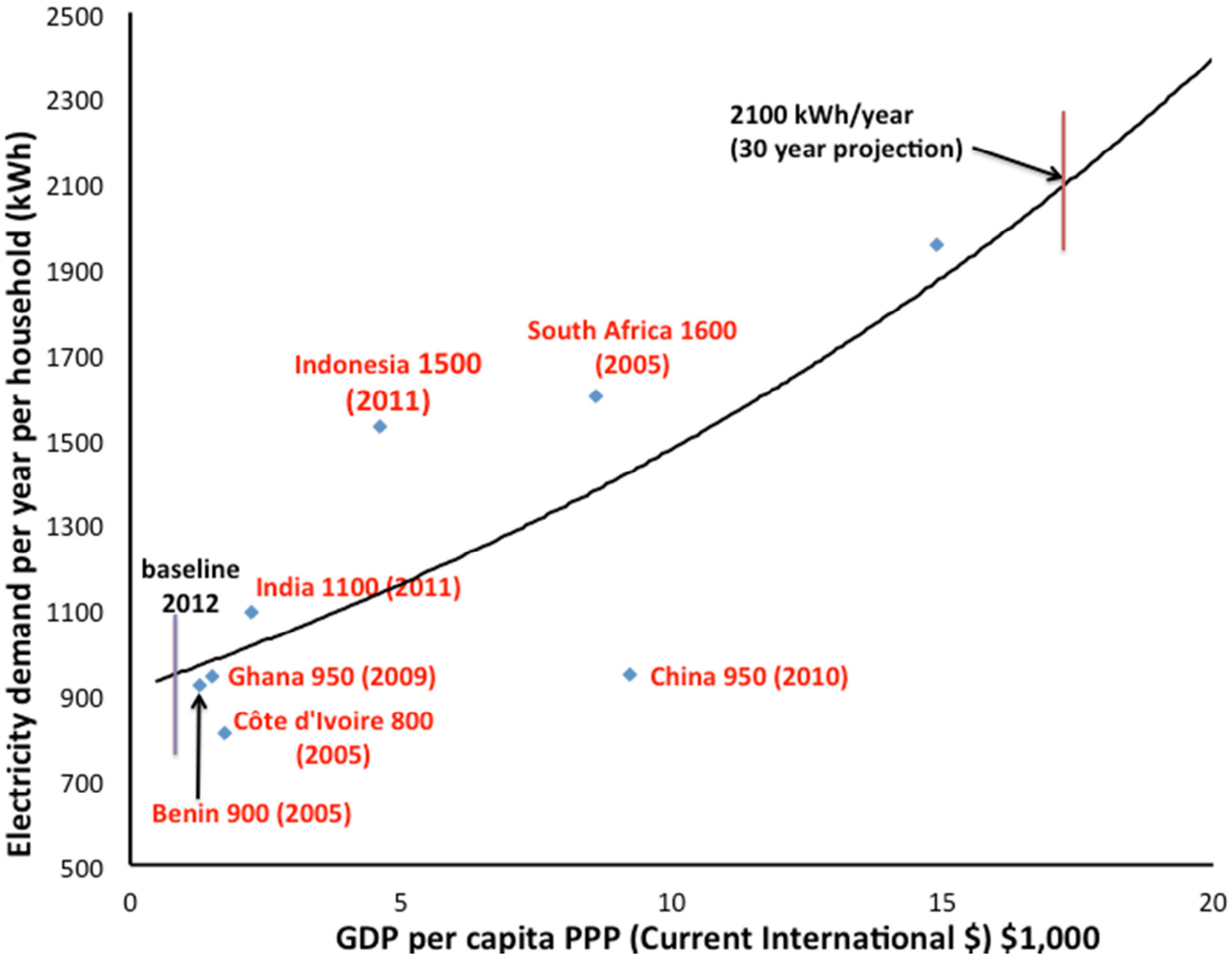

Figure 4: Household electricity demand for several developing countries, with GDP trend line.

A baseline electricity demand for Liberia is indicated on the figure based on the 2012 GDP. The predicted future national average value, of 2,100 kWh per year is marked along this same trend line.

Although Liberia's present day GDP per capita is quite low, around $600 per capita, as the economy continues its rebound, the country has experienced a very strong annual GDP growth rate. Nonetheless, it is unlikely that the rural-to-urban range of household demand provided here under-estimates residential demand in Liberia. Particularly as access expands to poorer areas of Monrovia, smaller and poorer cities, and much poorer rural areas, the average household demand seems likely to fall, at least in the short term. It is a greater risk to this modeling effort that the demand estimate, particularly with future demand projections, is too high. On this point, it is important to note that both productive, and perhaps more importantly, commercial sector demands have been excluded from this national estimate, the latter due to a lack of data on locations. In part to compensate for the absence of commercial demand, the approach here has been to allow a higher residential estimate.

3.2. Demand from Social Infrastructure: Education and Health Sectors

The estimated energy demands of Liberia's health facilities are presented in Table 7 below. These are based on a combination of sources, including: information from Liberia's own health plans and documents; prior electricity analysis work by the World Bank; LEC billing records from the John F. Kennedy Medical Center in Monrovia; and general USAID electricity data for health facilities. Demands quantified based on data laid out by a USAID report[22] and information gathered by Kris Stroup for the 2011 World Bank Liberia Energy report[23], with reference to the equipment lists given in the Primary Care facilities[24] and Hospital Package[25] documents. In some cases, the values were adjusted upward, either due to evidence from billing records or if it appeared that load requirements omitted electricity demands of HVAC and refrigeration. As with residential demand, the health demands were assumed to triple over the 30 year time horizon, since populations served by existing facilities will grow, and more extensive medical technology in use.

Table 7: Electricity Demand Estimates for Health Facilities

Facility Type	Clinic	Health Centers	County Hospital	Regional Hospital
No. of Beds	0	40	varies	250
Electricity Demand Estimates (kWh/yr)				
USAID (Powering Health)	1,594	3,669	17,358	63,391
Final Model Input	**2,000**	**2,000**	**60,000**	**100,000**

The locations of current and future health facilities are mapped out in the 10-yr health Plan[26]. In this model, County and Regional healthcare centers are treated as stand-alone nodes (with their own geospatial coordinates and electricity demand estimates) while clinics and health centers are geospatially merged with, and electricity demand summed with, the nearest residential community.

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[22] USAID. Powering Health: Electrification Options for Rural Health Centers. Appendix A

[23] October 2011. The World Bank Group. Options for the Development of Liberia's Energy Sector: AFTEG Energy Sector Policy Notes Series

[24] June 2011. Republic of Liberia Ministry of Health and Social Welfare. Essential Package of Health Service: Primary Care: the Community Health System. Phase 1 Report, Section 5.3

[25] November 2011. Republic of Liberia Ministry of Health and Social Welfare. Essential Package of Health Service: Secondary & Tertiary Care: The District, County and National Health Systems. Section 5.0

[26] July 2011. Republic of Liberia Ministry of Health and Social Welfare. National Health and Social Welfare Policy & Plan 2011-2021

Demands for educational facilities were assumed to be much more limited: 600 kWh/year for both primary and secondary schools, and 1,000 kWh/year for a school that combined both primary and secondary schools in a single facility. Despite the high importance and value of health and education electricity demands, the total electricity requirements for these sectors add to less than one percent of national demand, projected over 30 years.

3.3. Key Cost Assumptions for the Three Electrification Technology Options

The model considers three main technologies as electrification options for each community: the utility grid, a local diesel mini-grid, and power from a solar photovoltaic system. Select major cost drivers for each technology are listed in Table 8 below[27], along with the sources of data.

Table 8: Cost parameters for electricity from three electrification technologies (grid, diesel mini-grid, solar PV)

System	Category	Data Sources	Model Settings
LEC Grid	Electricity Supply (Busbar Cost)	• LEC Electric Master Plan • AICD Report ($0.08-$0.17)	$0.15/kWh
	MV Connection to Community	• LEC Sinkor Project Budget ($47/m) • Industry standards	$40/m
	Household Connection Costs	• LEC Sinkor Project Budget ($176/conn)	$125/Household
	Transformers	• LEC Sinkor Project Budget ($25-245/kVA)	$105/kVA
	MV Local Distribution Wire	• A per household distance of 15m was used with $40/m for wire + poles	$600/Household
	O&M Costs	• Fraction of initial investments	1% of line cost 3% of Transformer cost
Diesel Mini-grid	Generator	• Default value + local expert input	$165/kVA +25% installation
	Fuel	• Discussion with local experts	$1.20/L ($0.48/kWh)
	Generator Replacement	• Lifetime of generator	$30/kVA/yr
	Household Connection Costs	• LEC Sinkor Project Budget ($176/conn)	$100/Household
	Distribution Wire	• A per household distance of 15m was used with $40/m for wire and poles	$600/HH
	O&M Costs	• Default value + local expert input	10% of initial costs
Off-Grid Solar Photovoltaic	Solar Modules	• RREA industry research ($3.5/W)	$1.509/W (installed)
	Battery Storage	• RREA industry research ($213/kWh)	$213/kWh
	Battery Sizing	• HOMER design analysis	7 kWh/kW
	Battery Lifetime	• Industry research	2.5 years
	Replacement costs	• Default value + local expert input	$0.10/kW per yr
	O&M	• Default value + local expert input	2% of initial costs

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[27] Note that a full list of all model parameters, including costs not listed here, are presented as an appendix.

Whenever possible, local data sources for projects recently completed (such as one in the Sinkor neighborhood of Monrovia) were used to ensure that the model reflected local costs. For some model parameters little local cost information could be found. In these cases default values or information from other similar projects in other countries were used, following discussion with local experts.

LEC's unusual distribution topology extends medium-voltage (MV) lines to numerous small transformers near the final connection, then employs low-voltage (LV) line only for the service drop (see Figure 5 below). This design is expected to reduce theft since service drops originate from a single pole mounted transformers installed above the medium voltage line and equipped with split pre-paid metering. For this reason, there are two separate medium-voltage (MV) wire costs to be considered in the model. The first is the "MV Connection to Community" and represents the cost of MV wire to span distances between communities. This is expressed in the table above only as a per meter cost, since the length of MV line between communities is determined by iterative geospatial modeling in the software. The second, "MV Local Distribution Wire" is a local cost, representing the length of MV wire required to span the distances between homes within a community.

Figure 5: Example of MV Distribution Approach of LEC using dedicated drop down lines.

4. Model Results

The approach used for Liberia has been to devise a least-cost electrification plan for meeting Liberia's energy demands over a 30 year time horizon. One output of the model is a list of the least-cost electricity type – grid, diesel mini-grid, or solar photovoltaic – for each location. The second output is an optimized grid path, or minimum spanning tree, which interconnects every location designated for the grid at the lowest total cost and without any loops.

Figure 6 below shows the result of the 30 year demand projection, in which roughly 90% of the national population is designated for grid access. The map includes all grid that was pre-existing (or planned for the very near term, such as the cross-border extensions and the CLSG line), newly proposed grid, and diesel mini-grids or solar photovoltaic systems, typically for more isolated locations with lower demand.

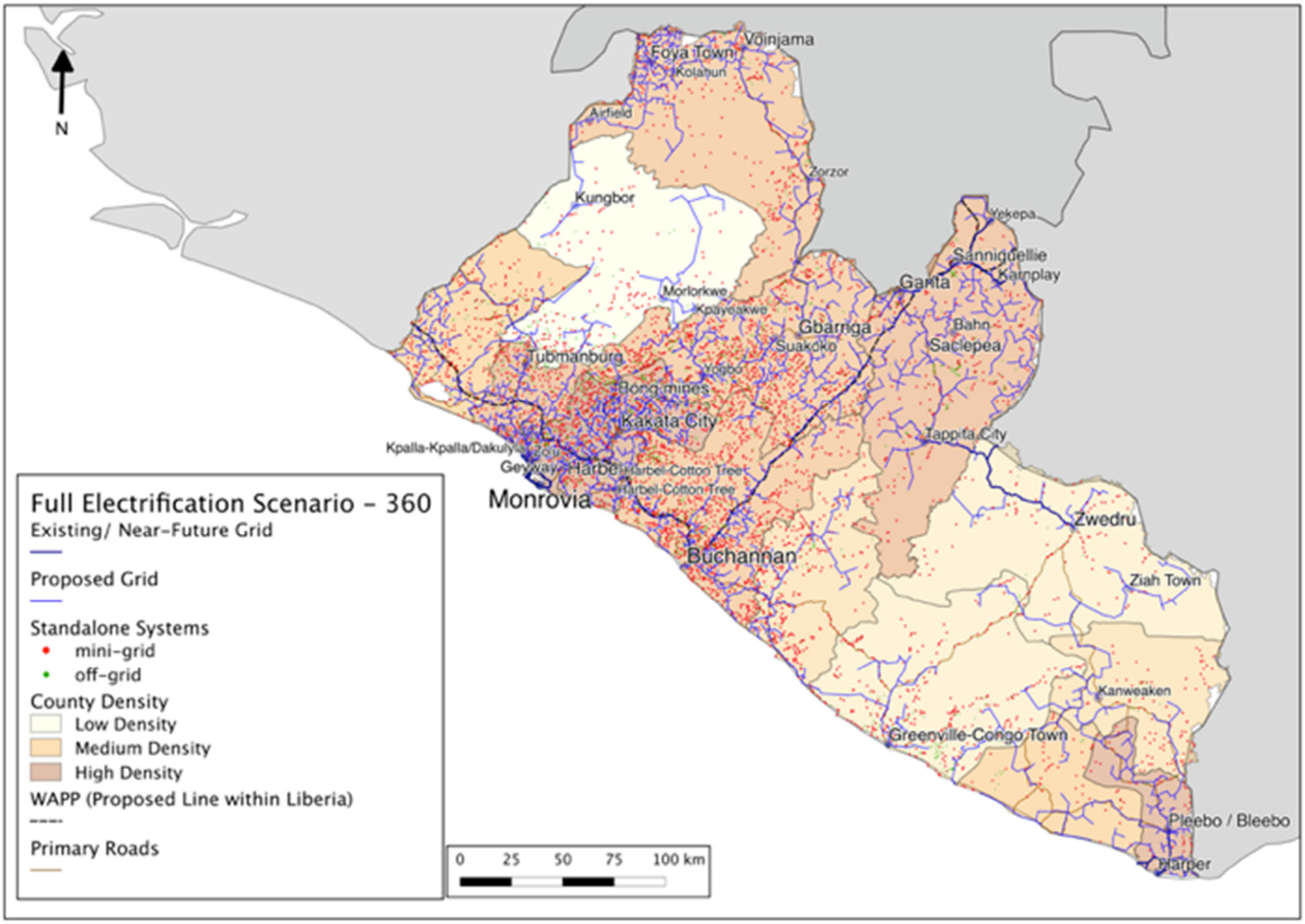

Figure 6: Final model result for 30 year electrification plan, including grid, mini-grid and solar PV system locations.

The details of this national electricity plan will be elaborated in the following sections, including initial costs, technical metrics, and sequenced roll-out in which full national electricity access is reached in three phases. However, in summary:

- The grid system presented here will, after 30 years, reach approximately 800,000 homes at an initial cost of roughly US$1,300 per household, or a total of approximately US$1 billion.

- Those locations (~10% of Liberia's settlements) for which stand-alone power options are ultimately the most cost-effective can be served by diesel mini-grids and solar PV systems for a total cost of around US$50 million.

- Geospatially, grid electrification typically begins with the largest communities (most are noted on the map by name), and extends to smaller communities, following routes that depend upon distance between settlements and their demand.

- Grid is most pervasive within counties with the highest population density, largely following the high-population corridor through Liberia's center, and reaching areas near coasts and international borders. Other locations further inland are reached by the grid, typically due higher demand at a population center such as a county capitol or site for resource extraction.

- The total peak electricity demand for the electricity grid as a whole is predicted to reach roughly 500 MW in 30 years. Additional insight for planning may be gained by examining expected peak demand aggregated at the county level, shown in Figure 7 below. The system is overall dominated by Monrovia, within Montserrado County, which has an expected demand of 395 MW or 77% of total system demand.

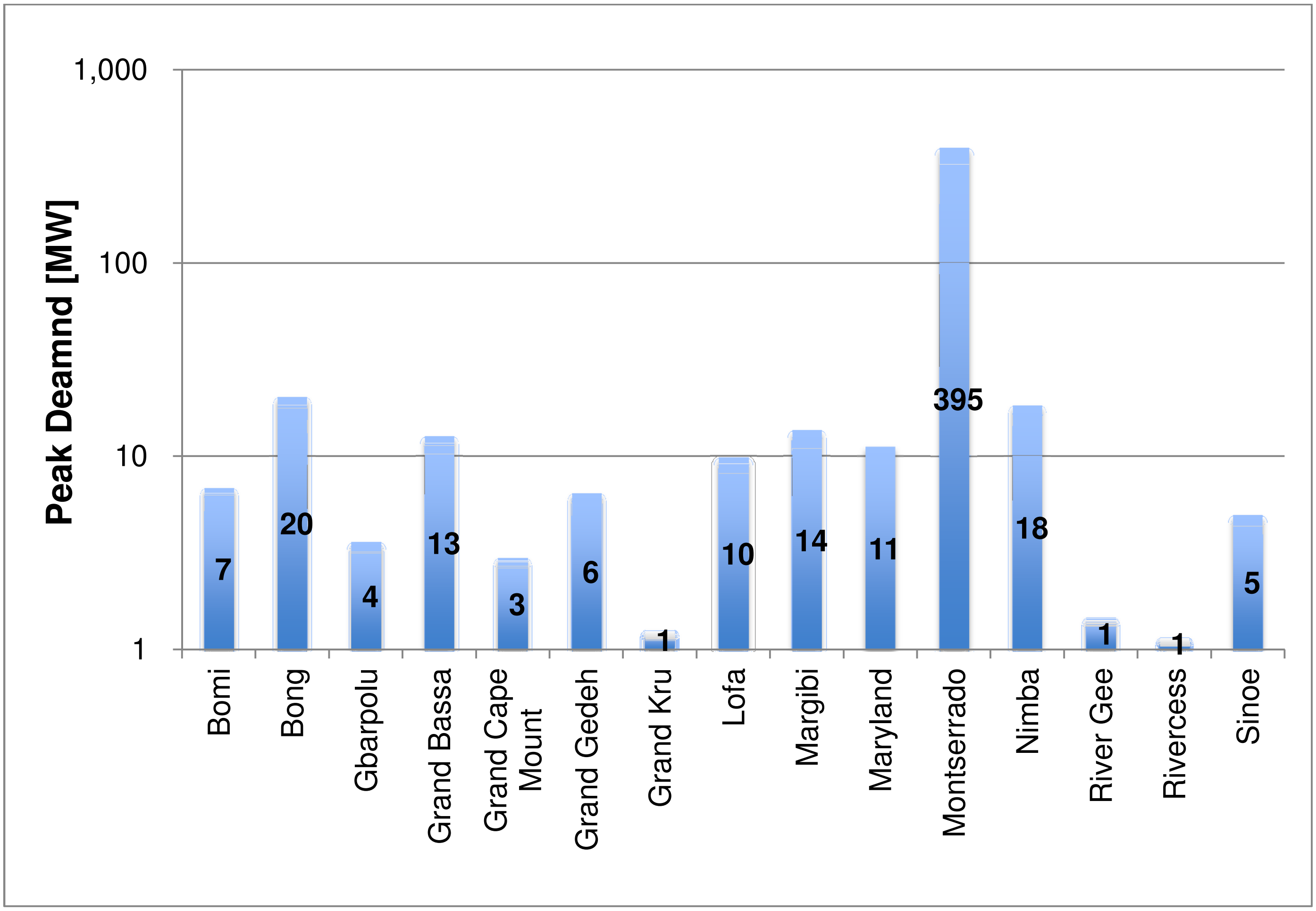

Figure 7: Peak Electricity Demand, by County, after 30 years (in MW).

4.1. Sequencing

To facilitate prioritization among the investments that will have the highest impact, this 30 year national scenario has been analyzed to provide a three-phase sequenced roll-out plan for investments in grid and stand-alone power systems. These phases correspond to the first 5, 15 and 30 years respectively of the 30 year program.

Several key investments that are planned or in-progress under pre-existing frameworks will be undertaken as preliminary work, lasting until approximately 2016. This preliminary work includes construction of WAPP line and related substations; construction of the Mt. Coffee hydroelectric dam; and ongoing intensification within and near Monrovia. A key assumption of the roll-out plan is that power needs will be addressed progressively, in two ways. First, grid extensions will emanate from existing grid infrastructure, whether part of the pre-existing Monrovia system or new locations as part of the cross-border or CLSG lines. Second, smaller "municipal" electricity systems will be introduced at the most populated, urban centers. The latter will be built to the same distribution specifications as the LEC Monrovia grid to allow for future interconnection. As a result, the pattern of grid construction is planned to gradually extend to new communities in a manner that results in separate grid progressively consolidating into larger systems.

Points of Origin: Following preliminary construction work, the grid system will include 7 primary points of origin (see Figure 2 for map locations):

- Monrovia LEC system
- Mano Substation (CLSG – WAPP)
- Buchannan Substation (CLSG – WAPP)
- Mt. Coffee Hydroelectric Dam
- Yekepa Cross Border & Substation (CLSG – WAPP)
- Zwedru Cross Border
- Harper Cross Border

In addition to these points of origin, this model has identified 19 communities – those which have 5,000 persons or more as of the 2008 Census, and thus meet LISGIS definition as “urban” – as sites for installation of municipal grids. These also serve as points of origin in the model. A complete list of such municipal grids can be seen in Appendix A.

Sequencing algorithm: A roll-out sequencing algorithm has been employed to ensure that incremental grid extensions prioritize connection of communities in a manner that balances the cost of incremental extension with the benefit of electricity delivered. The algorithm evaluates each segment of the total, 30-year national grid plan for Liberia, and prioritizes construction of the segments as follows: The algorithm starts from the pre-existing grid, and evaluates the benefit of connecting all locations neighboring the grid according to the ratio of each location’s electricity demand divided by the length of Medium Voltage line needed to connect it. The location with the highest ratio is connected. Then this process of evaluation and connection is repeated, for every segment in the grid. The result is a prioritized list of grid segments.

The grid plan for Liberia includes several thousand segments, originating from multiple starting points (listed above as “points of origin”). To create a simpler and clearer road-map for implementation, the total grid plan has been divided into three separate roll-out phases. These three phases show the process of grid expansion from multiple points of origin, followed by consolidation of separate smaller grids into larger and more unified grid.

- Phase 1, Years 0 - 5: Construction of 14 municipal grids and expansion of existing grid (Monrovia, CLSG substations and Cross-Border Systems);
- Phase 2, Years 5 - 15: Consolidation of expanding municipal grids into 7 larger systems and further grid expansion;
- Phase 3, Years 15 - 30: Consolidation into one interconnected grid with 6 major feeders.

	Generation at the end of each phase (MW, cumulative)			
Grid System (at start)	**Phase 1**	**Phase 2**	**Phase 3**	**Grid System (at 30 yrs)**
Buchanan CLSG Substation	2.1	5.0	17.3	Buchanan Substation
Bong Mines Municipal Grid	0.4	1.0		
Greenville Municipal Grid	1.1	2.1		
Harper / Côte d'Ivoire Cross Border	2.7	6.0	16.8	Harper / Côte d'Ivoire Cross Border
Ziah Town Municipal Grid	0.5	1.0		
Monrovia System	45.4	140.6	436.6	Monrovia System
Harbel Municipal Grid	0.5			
Kakata Municipal Grid	0.5			
Suakoko Municipal Grid	0.2			
Kpayeakwe Municipal Grid	0.2			
Yogbo Municipal Grid	4.2	8.8		
Tubmanburg Municipal Grid	0.2	0.5		
Yekepa CLSG Substation / Guinea Cross Border	2.3	9.6	35.8	Yekepa CLSG Substation / Guinea Cross Border
Gbarnga Municipal Grid	1.1			
Kungbor Municipal Grid	0.1			
Zorzor Municipal Grid	0.2	0.6		
Voinjama Municipal Grid	0.2			
Foya Town Municipal Grid	0.9	2.6		
Zwedru / Côte d'Ivoire Cross Border	0.8	2.1	5.7	Zwedru / Côte d'Ivoire Cross Border
Mano CLSG Substation	0.2	0.5	1.5	Mano CLSG Substation
TOTAL Generation (MW)	**66**	**181**	**514**	**Interconnected National Grid**

Figure 8: Pattern of grid consolidation over three phases, with increasing generation capacity by system and total.

This process of gradual consolidation of smaller grids toward larger systems is shown in detail, with indications of generation required to meet peak demand for each phase, in Figure 8 above.

The decision to progressively increase the span of time for each investment period is intended to reflect the tendencies of both electric utilities and energy ministries to plan somewhat differently depending upon the time horizon. Thus, Phase 1 -- with a relatively brief period of 5 years, starting around 2015 – is intended as a near-term plan, responsive to practical needs of policy makers and utilities for budgeting and planning. Phase 2 -- with a 10 year horizon, beginning around 2020 – should be seen as a mid-term plan, with greater uncertainty particularly in cost details, while still providing an overall geographic and technical framework for investment in grid and stand-alone technologies. Finally, Phase 3 -- with a 15 year time horizon, beginning around 2030 – is a long-term plan, with relatively high uncertainty, in part due to the difficulty of knowing key parameters like growth rates and costs, far in advance.

This roll-out plan projects approximately 90% grid connectivity after 30 years, leaving 10% that is predicted to be most cost-effectively served by standalone power, remaining off grid, even over the long term. However, this leaves a question of how best to serve those populations who will not be reached by the grid in the short-term, perhaps for decades, as the grid is being construction. As will be detailed in later sections, the approach proposed here is that these communities be served with temporary stand-alone systems – either diesel mini-grids or solar systems – as they await grid access. The total costs of this will depend largely upon the service standards – particularly the anticipated household electricity demand – to be met by these temporary systems.

What follows is a sequential presentation of maps for each phase, highlighting the broad geo-spatial and cost trends that dominate in each phase.

Phase 1, Years 0 - 5

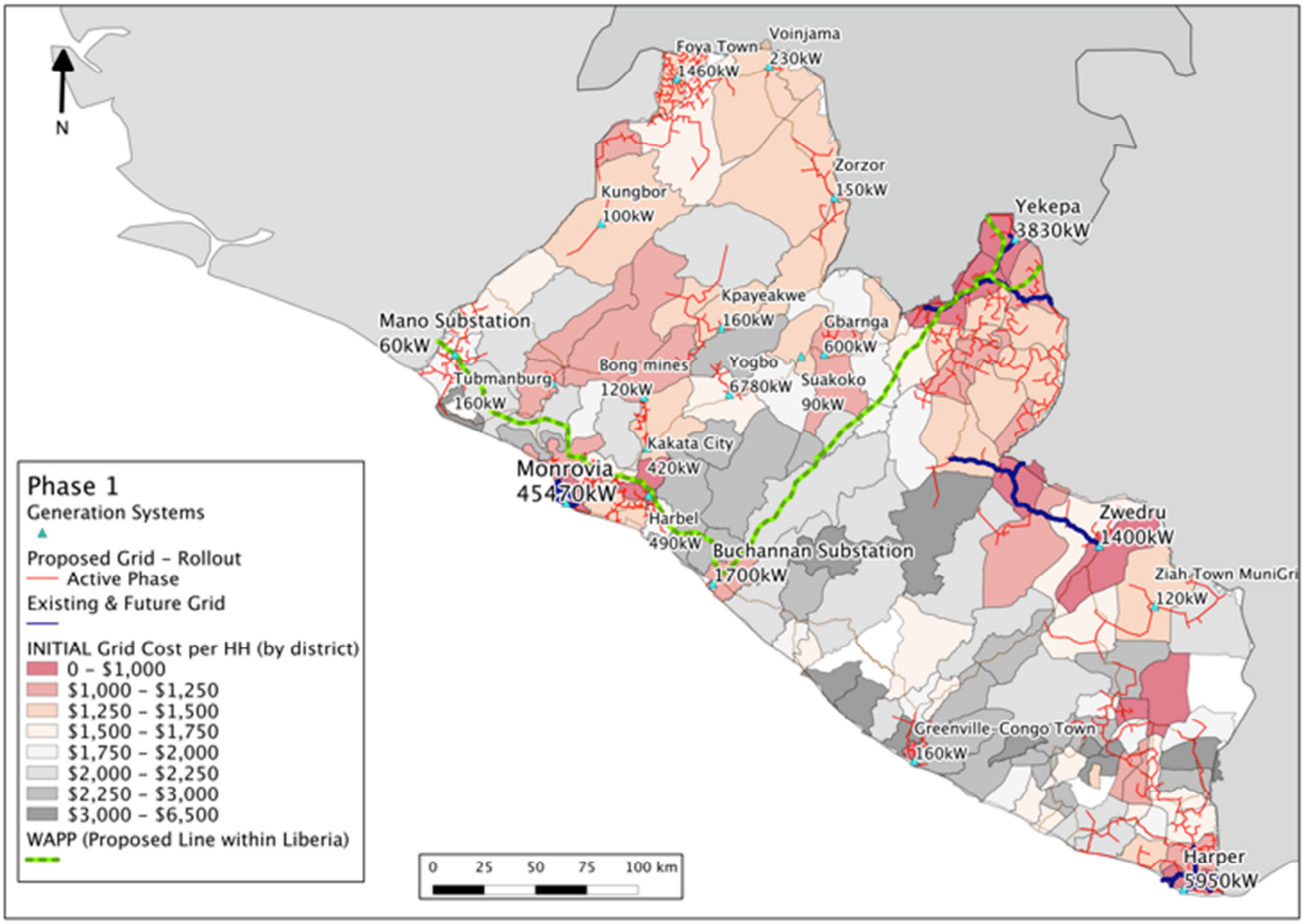

Figure 9: Grid roll-out for Phase 1, years 0 - 5, starting around 2015. Proposed grid extensions are shown in red.

Figure 9 illustrates a national approach for extending service as suggested in Phase 1. The map shows all pre-existing grid in dark blue. The planned CLSG (WAPP) line is shown in green, but the line itself is provided for reference only since no proposed MV grid lines originate directly from the CLSG HV lines. Instead, new MV grid originates only from predetermined CLSG substations as shown in Figure 2. New suggested grid paths for the phase of reference can be seen in red, which all originate from existing grid systems, CLSG substations, or urban centers as defined by LISGIS. The background of the map shows Liberian districts categorized by the relative cost to electrify households where red districts are the most cost-effective and gray districts indicate the least cost effective ones.

Overall, in Phase 1 the most cost-effective households are recommended for grid connections over an initial 5 year period assuming investment costs are kept relatively equal on a per year basis. Most MV expansion efforts in this phase focus on the establishment of 14 independent power systems centered in urban areas as well as intensification of customer bases for existing power systems. There is some in-filling suggested for districts that are quite cost effective and will quickly add to the LEC customer base. In this way the maximum amount of customers can be added for the lowest initial investment.

- Phase 1 reflects 5,000 km of new inter-community MV lines needed to connect 236,000 households. On a per year basis, such an effort would require installing 1,000 km and 47,000 households per year.
- This phase begins with 20 MV grid-systems whose locations, names and predicted peak demand can be seen in Figure 9. Six of these systems originate from areas with established generation sources such as CLSG substations or the existing Monrovia system. However 14 systems are independent and centered in urban areas currently unserved by any formal electricity system. These independent systems will not only need to build new distribution infrastructure but also the power generation capacity to serve the new demand base. It remains to be seen whether the generation sources come from diesel generators or hybrid systems incorporating hydro and solar resources in the region; resource studies being undertaken by LISGIS and the RREA may help to better inform the design of such generation systems.
- In subsequent phases, it is expected that these independent systems will consolidate into the national grid so that such generation facilities will either retire or relocate their higher-cost diesel generators or add renewable and hybrid generators to the distributed power mix of Liberia. Expected demand for these systems range from low peak demands of 100kW in Bong Mines or to a maximum, for Monrovia, at nearly 45MW.
- Phase 1 focuses mostly on intensification within Monrovia and extensions throughout Montserrado County, along with the establishment of 14 new urban demand centers most notably in Lofa County around the municipal centers of Foya Town and Voinjama.
- It is important to note that Phase 1 construction is largely concentrated in districts colored red or orange, where costs per connection tend to be below $1,500. This helps the utility to quickly achieve a larger customer base effectively growing their operations to a more sustainable scale.

Phase 2, Years 5 - 15

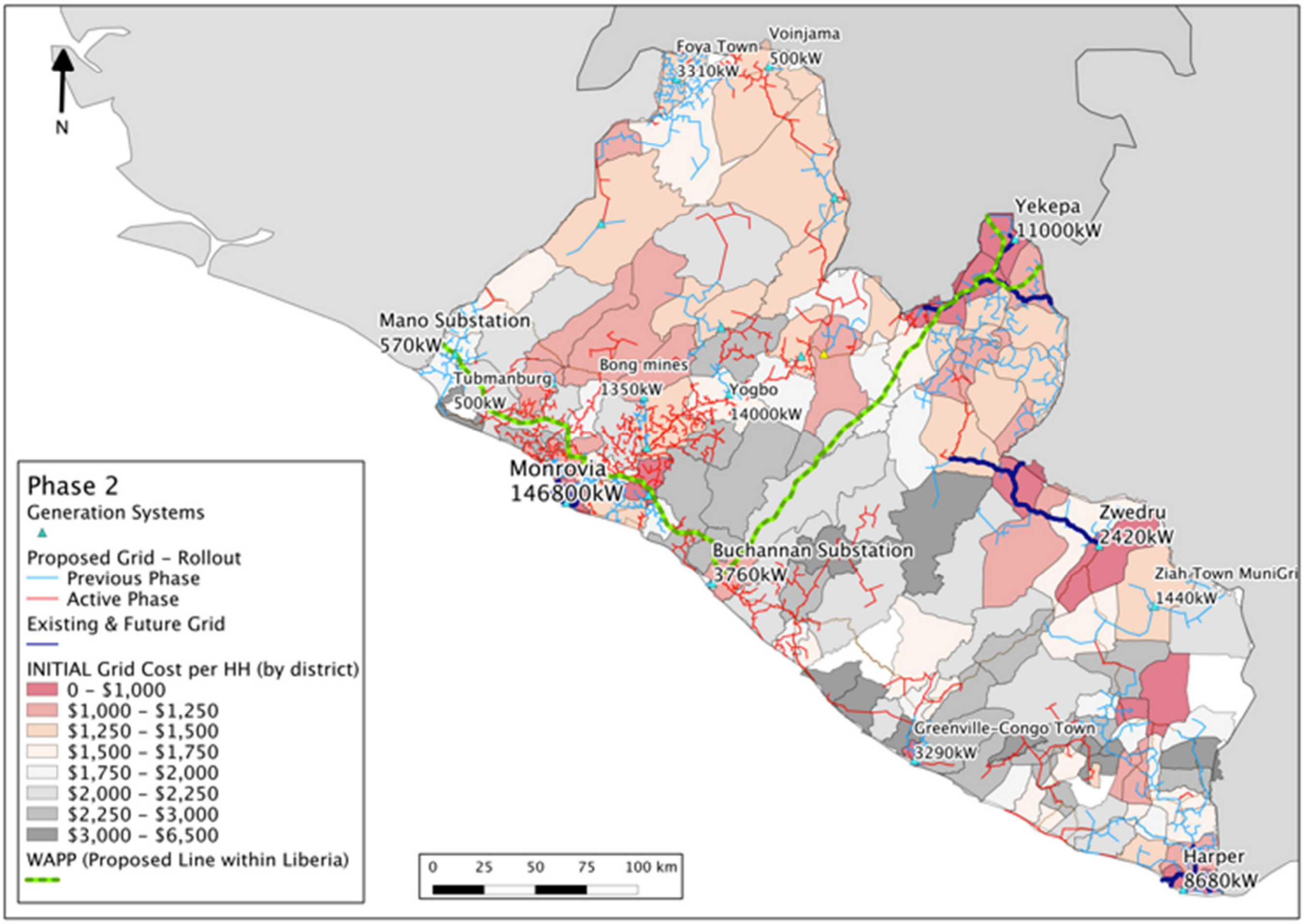

Figure 10: Grid roll-out, Phase 2, years 5-15, to begin around 2020. Proposed grid extensions in red, existing grid (Phase 1 and before) in light blue.

Figure 10 illustrates the new grid extensions suggested in Phase 2, assuming connections predicted for Phase 1 are already established, shown in this map as light blue line. Phase 2 should loosely span 10 years or years 5-15 of a 30 year investment strategy.

- Figure 10 reflects the construction of 4,608 km of proposed MV grid, or about 460 km of new distribution lines per year. Construction in Phase 2 centers on building out the region of high densities of population and electricity demand along the Monrovia–Gbarnga–Yekepa corridor, as well as a coastal corridor heading south from the Buchanan substation. A total of 227,000 households are expected to come on line throughout Phase 2.

- The number of independent grid systems starts to decrease in this phase, as the original 20 systems consolidates to 13. There is a predicted consolidation and expansion effort that begins in Phase 2 as Zorzor, Kungbor and Gbarnga are now fed by the linked to the Yekepa CLSG substation. The six independent systems that remain are Bong Mines, the coastal city of Greenville, Yogbo, Tubmanburg, Foya Town and Voinjama. The electricity demand for these independent systems also grows in response to population and economic growth. For example, Foya Town will see a growth in demand from 0.9 to 2.6 MW but will remain independent of the larger grid due to its geographic isolation.

- It is also useful to note that the mean household connection cost in Phase 2 increases to $1,437 from $757 in the prior phase. By Phase 2, few low cost 'red' districts see additional grid development as low-cost extension opportunities are exhausted in these areas, and construction shifts instead to higher cost orange and white districts.

Phase 3, Years 15 - 30

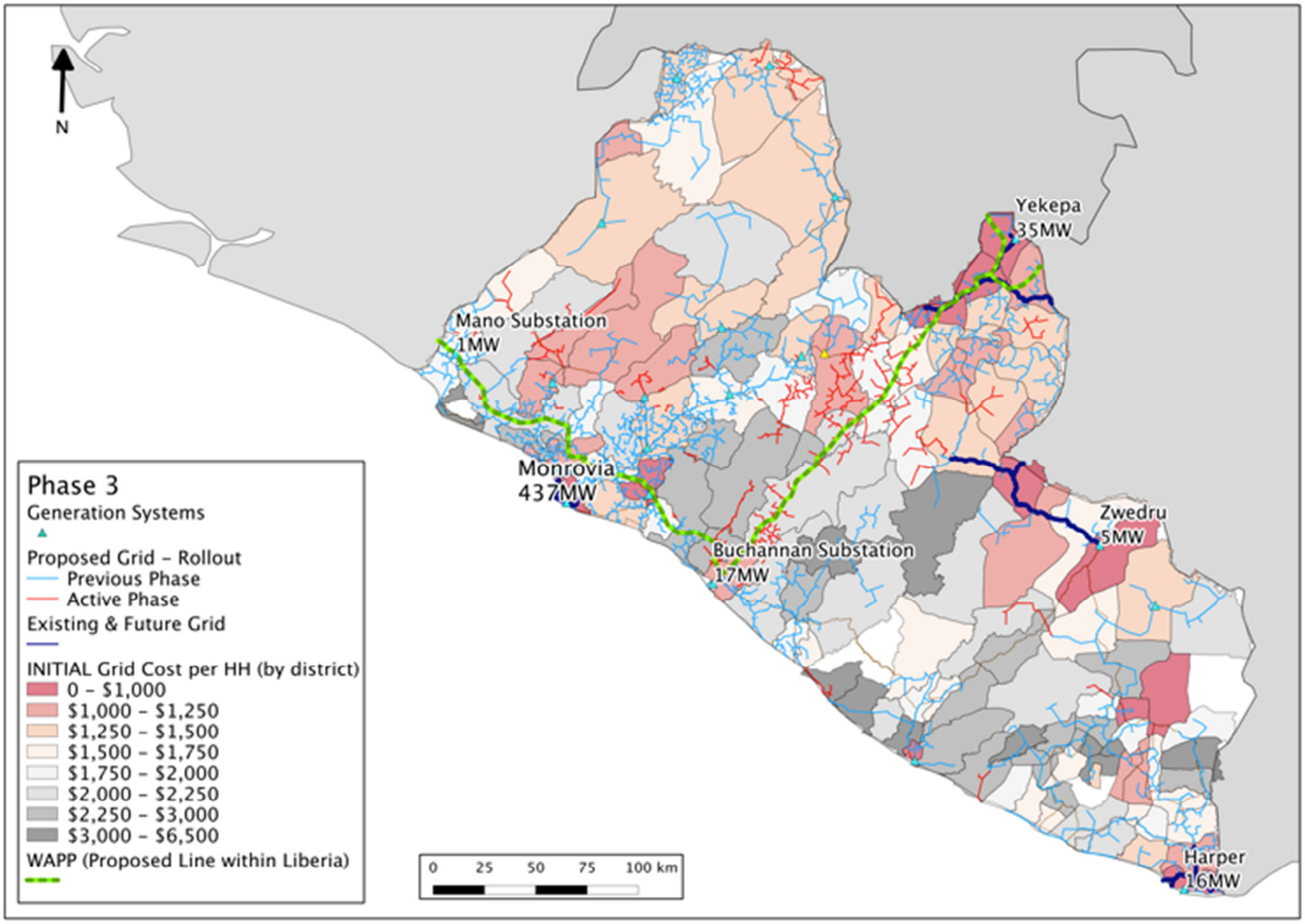

Figure 11: Grid roll-out, Phase 3, years 15-30, starting around 2030. Proposed grid extensions in red, existing grid (Phase 2 and before) in light blue.

Phase 3 as depicted in Figure 11 shows the final 15 years of a 30 year intensive electrification process. Prior electrification, for phases 1 and 2, is shown in light blue lines while all new construction is represented by red grid lines.

- A total of 2,338 km of MV grid lines (red) are needed to reach nearly a 90% grid-electrification rate for Liberia. Over a 15-year period, this would require about 160km per year of MV line build out towards either rural areas, interconnection spans or for last-mile communities.

- Phase 3 sees the complete consolidation of independent power systems into six parent systems, which would likely be inter-connected. The Foya Town and Voinjama systems interconnect to the Yekepa CLSG substation, and the coastal town of Greenville joins the Buchanan substation feeder. It is likely that these independent systems will continue to operate independent generation systems but with greater stability and reliability stemming from a 2-way connection with the national grid.

- The greatest aggregate demand stems from the Monrovia system with 437 MW peak demand. The Yekepa substation is expected to meet nearly 35MW of demand, while the Harper cross-border and Buchanan substation systems both provide about 17MW of peak demand. Smaller systems on the Zwedru cross-border system, with a total of 5MW of demand, and Mano Substation, delivering less than 2MW, have relatively low output, even after 30 years' time, due to their largely rural demand bases.
- The majority of build out anticipated in this third and final phase will likely occur along the CLSG corridor traversing through Rivercess and Grand Bassa counties, where largely rural connections have higher cost (as seen by extensions in many white and grey districts). The rest of the active construction is more last-mile type connections or interconnecting independent systems into the national grid. For example, there are some expansions occurring in the North near Foya Town as well as from the Mano Substation.
- By this point, the average per household connection cost will reach $1,900 with many extensions rising to $2,500 per household. Due to these high connection costs, Phase 3 is considered the most speculative relative to the other planning and investment phases. Grid extension plans may be modified or scaled back by the time implementation has reached this stage, depending upon costs at that time for stand-alone options.

4.2. Summary of Results: Technical Metrics

The following section explores cost and technical summary data corresponding to the three-phase grid roll-out sequence presented previously. Costs reported are a consequence of underlying technical metrics such as a number of connections added per phase, energy demands (GWh) and peak demand capacities expected (MW). We explore aggregations and averages of these summary metrics by phase in Table 9.

Table 9: Metrics for new connections per phase

Base Case Results	**Target Household Count**		**House-holds connected per year**	**Total Peak Demand**		**Gen. Capacity Added per Yr**	**Peak Dmd per Household**		**Total Annual Demand**		**Annual Demand per HH**	
	(Thousands)		**(Thsds)**	**(MW)**		**(MW)**	**(W)**		**(GWh)**		**(kWh)**	
	cum.	**New**		**cum.**	**New**	**MW**	**cum.**	**New**	**cum.**	**new**	**cum.**	**new**
Phase 1, Years 0-5												
Total Grid	**236**	**236**	**47**	**69**	**69**	**14**	**290**	**290**	**250**	**250**	**1,070**	**1,070**
Monrovia System	141	141	28	45	45	9	320	320	170	170	1,180	1,180
Other (Non M'via)	95	95	19	24	24	5	250	250	90	90	920	920
Phase 2, Years 5-15												
Total Grid	**464**	**227**	**23**	**198**	**128**	**13**	**430**	**560**	**730**	**470**	**1,560**	**2,060**
Monrovia System	273	132	13	147	101	10	540	770	540	370	1,960	2,800
Other (Non M'via)	191	95	10	51	27	3	270	280	190	100	970	1,030
Phase 3, Years 15-30												
Total Grid	**790**	**326**	**22**	**514**	**316**	**21**	**650**	**970**	**1,880**	**1,150**	**2,370**	**3,530**
Monrovia System	517	244	16	437	290	19	840	1,190	1,580	1,050	3,080	4,330
Other (Non M'via)	273	82	5	77	26	2	280	320	280	100	1,030	1,170

A few broad observations are evident in these data:

- The rate of new households added to the grid is highest in phase one, at about 47,000 new connections annually and quickly drops to roughly half this figure, 23,000 per year, by phase 2 and remains at roughly this level through phase 3. This reflects the relatively low investment for grid electrification in the early phase of urban grid roll-out occurring in Phase 1.

- For all metrics – households added per year, as well as both peak and annual demand – the Monrovia area dominates the cost and technical planning for Liberia as a whole. However, the disparity between the metrics for Monrovia and other systems becomes particularly severe in the third phase, when both the number of new households connected and demand per household are nearly three times that of the rest of the system combined.

- The rate of the increase in demand per household is roughly 3 for Monrovia but only slightly above one for more rural areas. In addition, the total increase in aggregate demand for Monrovia rises by a factor of ten (from about 160 to about 1,600) over the three phases, while that of other areas rises only by a factor of around 3 (from around 90 to about 280).

This is due to the combined effects of faster population growth in urban areas, plus higher household demand in larger cities.

- Overall, perhaps the main point is to emphasize that the rate of adding connections is not sufficient predictor of demand growth, particularly in larger urban areas. Due to the rising rate of household consumption, there is also a need to continually increase electricity supply at a rate faster than what would be expected simply from the addition of new households to the system. As time passes, those new connections should be expected to start with a higher initial demand, while, at the same time, the demand of existing urban customers is likely to continue to grow rapidly.

4.3. Summary of Grid Expansion Results: Initial Costs

Table 10 below presents estimates for costs to bring Liberia to full electrification. Costs are for grid expansion over a 30 year time frame, in three phases, as presented above.

Table 10: Overview of grid expansion, cumulative households connected and cumulative costs for each phase.

	Target HH count	Initial Cost (MV + internal)		Proposed MV length		MV Costs	
	[1,000]	Total [$M]	per HH [$]	Total (km)	per HH (m)	Total [$M]	per HH [$]
Phase 1							
Grid Total	**236**	**$178**	**$757**	**2,992**	**13**	**$120**	**$506**
Monrovia System	141	$86	$612	1,407	10	$56	$399
Other (Non-M'via)	95	$93	$971	1,585	17	$63	$666
Phase 2							
Grid Total	**464**	**$506**	**$1,090**	**7,600**	**16**	**$304**	**$656**
Monrovia System	273	$215	$790	2,396	8.8	$96	$351
Other (Non-M'via)	191	$290	$1,521	5,204	27	$208	$1,091
Phase 3							
Grid Total	**790**	**$1,027**	**$1,300**	**9,938**	**13**	**$398**	**$503**
Monrovia System	517	$595	$1,150	4,253	8.2	$170	$329
Other (Non-M'via)	273	$433	$1,586	5,685	21	$227	$834

One of the most important overall summary metrics for grid electrification is the total initial cost per household connection. This metric includes all equipment and installation costs for establishing both the MV distribution grid that interconnects different communities and the local MV distribution system (as illustrated in Figure 5, presented in an earlier section), as well as all other local costs such as transformers, LV service drop to the home, household electricity meters, and installation fees. There is a rising trend throughout the 30 year time span, with initial costs of around $760 per home in Phase 1, rising to around $1,300, on average, for all homes nationally by the end of Phase 3. There is also a large discrepancy between initial costs per household on the Monrovia System versus all systems outside of Monrovia: in Phase 1, the per household cost is roughly 50% higher outside of Monrovia (about $970 versus $610). LEC provides cost estimates per connection, which are useful for validation, though only for Monrovia. The recent LEC master plan (2011), covering the next 4 years (roughly equivalent to the first phase the model presented here) gives a cost of $750-1,000 per connection, while values from our model of around $610 to $970, a fairly close agreement. Similarly, total costs for our model can be compared, at least for the first phase within Monrovia, with those from LEC. The LEC master plan plans for 4 years of investment at $20-25M per year[28], while these model results predict ~$86 M investment for Monrovia Phase 1; again, a close agreement.

For Phases 2 and 3, results are reported here only as cumulative values. This is because grid build-out projects can be undertaken for reasons that are not obviously cost-effective when viewed locally (i.e., when a connection of a specific settlement is along the path to a larger settlement), or over the short term (when a connection to a settlement is made, in part, anticipating future growth). As a result, incremental grid investments at the 10, 15, or 20 year points may diverge markedly from the long-term average, and appear, at the local level or over the short-term, to be not cost optimal, even if they are cost-effective at larger spatial and time scales. Thus, for new connections in Phases 2 and 3, specific connections may rise to $1,500-2,000, or more, particularly outside of Monrovia, though the national, long-term average works out to around $1,300 per connection.

Since the sequence of grid extensions prioritizes the highest electricity demand met by the lowest MV line length, the grid construction phases presented earlier tend to progress from high to low demand density areas, meaning from urban to rural areas. Table 11 below shows data on MV line and related cost to connect households in various geographic classes.

Table 11: Sequential grid-related MV expansion estimated outlays per projected households served

Area Categorization	Total MV Line Needed [km]	Households Connected [qty]	MV Line Per Household [m/HH]	MV Cost per Household [$/HH]
Greater Monrovia Intensification	1,360	394,000	3.5	$138
Urban Areas & Towns	3,250	288,000	11.3	$452
Rural Electrification and System Interconnections	5,320	107,000	49.7	$1,990
TOTAL	**9,930**	**788,000**	**12.6**	**$504**

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[28] Liberia Electricity Corporation. *Electric Master Plan.* March 2011 (pg. 21-23)

These classes do not correspond exactly with the three phases presented above, and instead represent electrification in and around Monrovia, connections in various urban areas and towns nationally, and finally rural electrification in more remote areas and interconnections to form a larger national grid system. There are two important observations from this table: First, the broad trend is clearly from short distances and low MV costs in urban areas (under 4 m of MV line, and around $140 per connection) toward longer distances and higher MV cost in more rural areas (around 50 m per connection, costing nearly $2,000). In short, rural electrification is clearly more expensive, largely due to the distances covered between communities and households.

It may be counter-intuitive then to consider that, according to the model projections with all initial and recurring costs over the full 30 year time horizon, even these high cost grid extensions into rural areas are less costly over the long-term than stand-alone diesel or solar PV systems *assuming that all three systems – grid, diesel and solar – must meet the same electricity demand.* The last phrase is essential, because it is not necessarily applied in all many national electrification programs. For instance, in recommending or providing small solar home systems for rural residents, many rural electrification schemes are determining, perhaps implicitly, that power demands for rural users will be met at what is typically a much lower standard.

The approach taken here has been to assume a common demand framework across all households nationally – i.e., by using a logistic curve to estimate household demand as described in section 3.1. However, this is not always practical, given budgetary and other constraints for grid extension programs in the face of short-term power needs for rural residents.

The next section of this report describes how to address rural demands through roll-out of stand-alone diesel or solar PV systems, whether as a long-term solution for power needs in remote areas, or as temporary measure.

4.4. Summary of Standalone Systems by Phase

The overall planning approach used here includes calculation of full, long-term costs for three possible electricity system types – grid, diesel mini-grid, and solar photovoltaic – for every location in the system. The results shown in prior sections illustrate the plan for grid construction for those ~93% of locations nationally where grid electrification is the most cost-effective option overall. This leaves two categories of electricity demand which can potentially be addressed using standalone systems with diesel or solar PV generation: i) Around 7% of the national population will reside in locations that, due to remoteness or low total demand, are not cost-effective for grid connectivity even after the full 30 year national electrification program is complete; and ii) many locations will be targeted for grid connection, but remain without power, perhaps for many years, as the grid roll-out plan proceeds.

This “stand-alone” aspect of the electrification program assumes two types of systems – diesel mini-grids and solar photovoltaic off-grid systems. Aside from the generation, the main difference between the two is essentially scale: A mini-grid system has diesel generation, most likely centralized at the community level, and distribution through a local network built to standards that meet or approximate utility grid systems. In contrast, a community recommended for off-grid solar power will be served either by individual solar home systems or solar micro-grids, which include smaller, neighborhood-scale generation (for perhaps 1-3 kWp, supplying ~20 homes) with very small-scale and low-cost local distribution (essentially low-cost, dedicated wires on inexpensive poles to surrounding homes).

Table 12 below provides costs details for two broad types of standalone systems. The first are the “permanent” standalone systems, those serving locations that are not targeted for grid connections. The total costs for this aspect of the national electrification plan would be only about US$45-50 million across all three phases, or roughly $300 initial costs per household for diesel and $1,040 per household for solar.

Table 12: Overview of standalone power systems and costs per house

	Target Households [Thsds]				**Initial Costs (US$M)**				**Initial Costs per HH (US$)**			
System Type	**Ph1**	**Ph2**	**Ph3**	**Tot**	**Ph 1**	**Ph 2**	**Ph 3**	**Tot**	**Ph 1**	**Ph 2**	**Ph 3**	**Tot**
Diesel mini-grid	22	36	47	105	$4M	$9M	$19M	**$32M**	$186	$242	$405	**$305**
Solar off-grid	2.5	4.5	6	13	$2M	$2.5M	$9M	**$13.5M**	$739	$555	$1,514	**$1,040**
Temp. diesel mini-grid	66.5	38	0.0	104.5	$12M	$8.5M	$0	**$20.5M**	$176	$224	NA	**$200**
Temp. solar off-grid	1	0.5	0.0	1.5	$1.5M	$0.5M	$0	**$2M**	$1,658	$749	NA	**$1,330**
Grand Total	**92**	**79**	**53**	**224**	**$19.5M**	**$20.5M**	**$28M**	**$68M**				
Perm. Investment	24.5	40.5	53	118	$6M	$11.5M	$28M	$45.5M				
Temp. Investment	67.5	38.5	0	106	$13M	$9M	$0	$22.5M				
50% Temp. Investment					$6.5M	$4.5M	$0	$11M				

Note that, in order to make the cost-comparison equal in technical terms, these diesel and solar systems have been sized to meet the same household demand levels as the grid connections described in other sections. This may explain the apparently high costs per household of solar power described here versus the sorts of low-capacity solar home systems that many electricity practitioners are familiar with. These small, low-cost solar home systems are less expensive (typically between $50 and $200); however, they typically provide power at far lower levels than a diesel or grid connection.

Also, planners should bear in mind that the lower initial costs for stand-alone systems, particularly diesel, are balanced by high recurring costs compared to grid. These high recurring costs necessitate sound management systems that ensure cost-recovery, including not only relatively ordinary operations and maintenance, such as fuel and engine maintenance, but also less frequent re-investment, such as batteries for solar systems, needed every 2.5 to 3 years, on average.

The second set of cost details is for a “temporary” category of communities to be electrified with stand-alone systems as a stop-gap measure while communities await grid connection. This program would cost around US$22 million, or roughly one-third of the initial investment for the “permanent” stand-alone systems. This investment in temporary power systems would require a strong commitment, since there would likely be at least some political and budgetary concerns related to the fact that certain locations would, in effect, be electrified twice – once with a temporary standalone system, then again later with a grid connection which may be difficult.

Recognizing this, an additional line has been added to the table indicating the cost of electrifying these communities with a standalone system of only half-capacity, reducing this stop-gap investment by 50%. This “half-capacity” approach, combined with the inherently lower initial costs of these standalone systems relative to grid power, reduce the relative magnitude of expenditure for these systems to a total of $11M – less than one-fifth the 25% of the “permanent” stand-alone program, and around 1% of the total grid roll-out plan. Furthermore, communities served by these temporary systems should be expected to cover the full recurring costs of these systems, which may be eased a bit since the systems’ total expected life is limited, on the order of 5-15 years. At these lower cost thresholds, and with local commitment to covering recurring costs, it is likely that the political benefits of somewhat lower-capacity electrification balance favorably against the costs.

As noted previously, the cost-effectiveness of grid vs. stand-alone power systems has a strong geo-spatial component. Summary statistics for permanent standalone systems grouped by county, as provided in Table 13 below, can clarify investments needs and strategies in different parts of the country. These model results also show that around 10-11 MW of demand will need to be met by standalone systems. The majority of this demand is more cost-effectively met by diesel mini-grids, which are recommended for seven times the household demand and more than twice the number of communities relative to solar PV. The counties are ordered by the sum of peak demand, providing insight into which areas have relatively large demands that will not be met by grid extension. These are likely to be good targets for a variety of rural electrification efforts, including intensive renewable resource mapping as well as additional, more detailed stand-alone system planning and implementation, along the lines of what is currently being undertaken by RREA.

Table 13: Overview of permanent standalone power systems, households served and expected peak demand by County

County	Off-Grid Households [qty]	Off-Grid Communities [qty]	Off-Grid Peak Demand [kW]	Mini-grid Households [qty]	Mini-grid Communities [qty]	Mini-grid Peak Demand [kW]	TOTAL Peak Demand [kW]
Bong	1,605	439	293	8,692	944	1,598	1,891
Grand Bassa	1,174	319	214	8,969	1,020	1,657	1,871
Sinoe	466	127	85	3,843	332	728	813
Lofa	268	75	49	3,664	278	685	734
Rivercess	152	42	28	3,587	294	667	694
Nimba	492	141	90	3,088	253	582	672
Gbarpolu	321	88	59	3,027	192	567	625
Grand Cape Mount	247	70	46	2,852	246	529	575
Margibi	778	215	142	2,122	290	394	535
Grand Gedeh	53	15	10	2,494	124	467	477
Montserrado	676	190	124	1,864	276	347	470
Bomi	382	106	69	1,748	188	322	391
River Gee	41	12	8	1,656	92	312	320
Grand Kru	50	14	9	738	52	138	147
Maryland	30	8	5	584	35	109	115
TOTAL	**6,735**	**1,861**	**1,230**	**48,928**	**4,616**	**9,102**	**10,332**

Liberian energy planners note that communities near the high voltage CLSG line may benefit from induction connections without the expense of many step-down substations. A preliminary analysis begins below with a selection of communities that are located within 3 km of the CLSG line – but are not targeted for grid connection. A summary of these sites, by County, is reported in Table 14.

Table 14: County Assessment of communities proposed for standalone power systems that are within 3km of the CLSG HV transmission line

County	Off-Grid Households [qty]	Off-Grid Communities [qty]	Off-Grid Peak Demand [kW]	MiniGrid Households [qty]	MiniGrid Communities [qty]	MiniGrid Peak Demand [kW]	TOTAL Peak Demand [kW]
Grand Bassa	286	61	41	1,010	114	138	180
Bong	102	22	15	310	31	43	57
Montserrado	117	26	17	220	30	31	48
Grand Cape Mount	18	4	3	286	22	39	41
Bomi	69	15	10	201	19	28	37
Nimba	46	10	7	166	13	23	30
Margibi	-	-	-	7	1	1	1
TOTAL	**638**	**138**	**91**	**2,200**	**230**	**302**	**394**

The aggregate projected demand of these communities amounts to about 400 kW, or around 4% of the 10.3 MW peak demand projected for all standalone systems. An analogous sum of demand for communities that are within 3km of the CLSG line but are currently targeted for grid connections comes to 11.4MW, or slightly more than 2% of total grid demand (breakdown by county not shown). The potential settlements are shown in Figure 12 below . In both cases, the potential to substitute supply from the CLSG line for populations that can be reached by such induction represents a small, but significant portion of the projected demand that would otherwise be met by grid or stand-alone systems. This analysis suggests that, while this approach may help Liberia reach its access goals, particularly if this induction technology can be implemented quickly and at scale, it is not likely to have a decisive impact on overall electrification rates nationally.

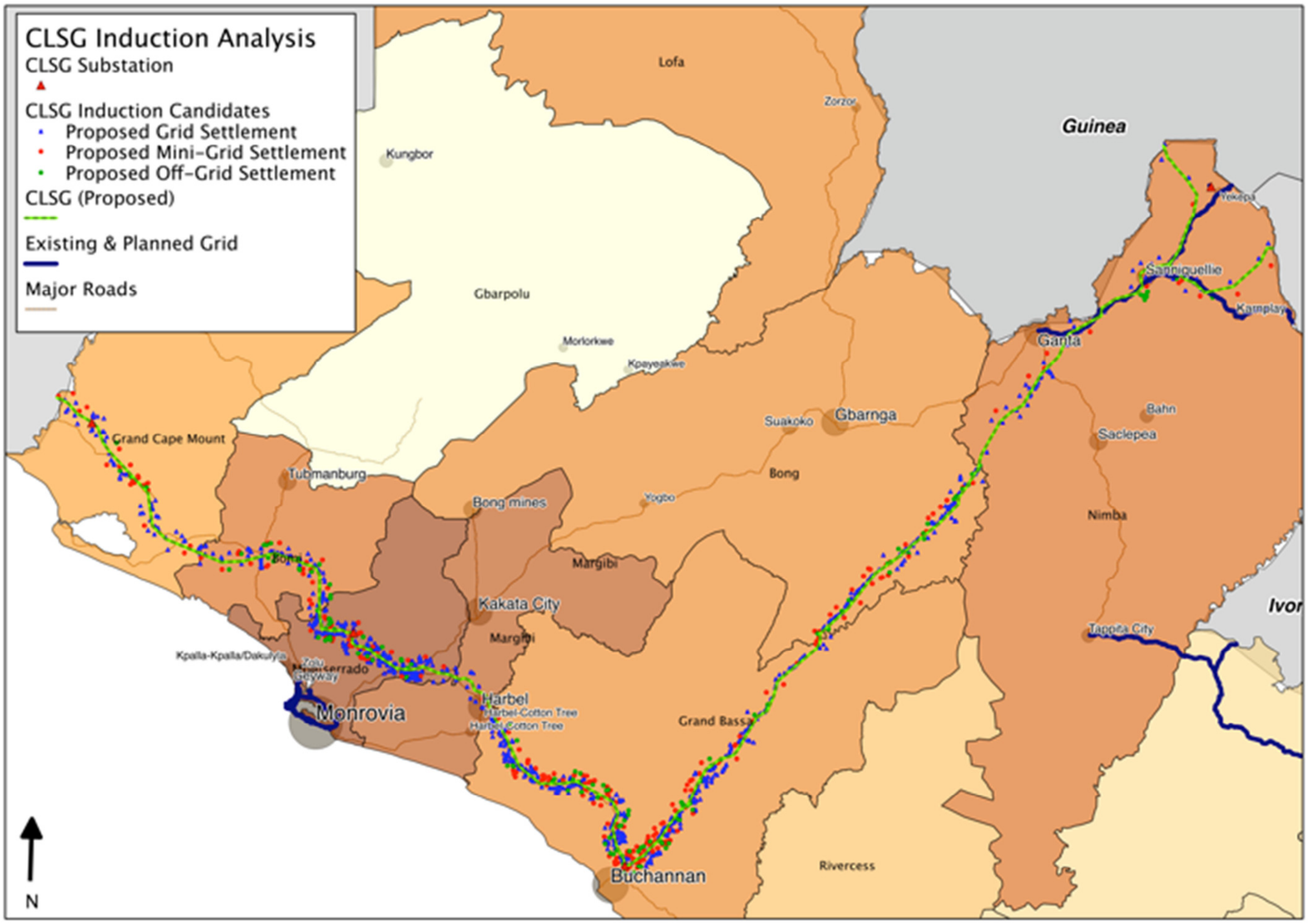

Figure 12: Settlements within 3km of proposed HV CLSG line within Liberia. This is a comprehensive depiction of communities that can potentially benefit from connections powered from HV induction loading.

5. Conclusions

This analysis has detailed an approach to estimating demand and costs for developing a geo-spatially detailed and cost-optimal electricity system to serve Liberia, reaching near universal access over the next 30 years. The report emphasizes the value of Liberia's detailed and accurate geospatial data, as well as the importance of establishing the best possible household demand estimate as a basis for projecting demand. The technical and cost projections provided here – of approximately US$1 billion for a national MV grid distribution system, and US$70 million for a mix of diesel and solar-powered stand-alone systems – depend essentially upon the quality and accuracy of these input datasets, demand estimates, and growth projections.

It is important, given the inherent limitations in input data and long timespans of these projections, to utilize the best possible growth figures while remaining modest about the accuracy of long-term predictions. Partly in recognition of these limitations, the results here are broken into phases of short-, medium- and long-term phases, with cautionary notes about the limits of long-term, detailed plans.

In short, it is advisable that local planners revisit these datasets, demand estimates and projections periodically, as data and assumptions change. The overall approach to this planning effort – which has included not only electricity master planning, but also training and capacity building in both field data gathering and data analysis -- was devised with localization of planning as a key goal.

In fact, research activities are already underway or planned within Liberia which will offer the potential for improvements in future planning efforts, including revisions of this master plan. These include the following:

- LISGIS is planning data gathering key demand points, including not only key public infrastructure such as police stations, border crossings, and government offices, and government facilities, but also markets and commercial centers. As has been noted previously, commercial sites are a crucial part of Liberia's overall electricity planning which should be included in future iterations.

- RREA, in coordination with others, is undertaking resource mapping and planning for renewable systems. Renewable and stand-alone power systems represent one of the major areas where a national electrification master plan such as this can be refined over time. Particularly as mapping and engineering work is done to characterize the locations and magnitudes of many important gut geographically specific electricity resources, this data can feed into improved geo-spatial planning in a variety of ways. This can, in the short term, provide geospatial information for power supply for stand-alone and municipal grid systems which might otherwise be reliant upon higher-cost hydrocarbon fuels. Over the medium-to-long-term, geo-location of renewable resources can also inform larger-scale grid planning, particularly as it affects the bus-bar costs of grid power, improving the potential for wider access.

- MLME has planned and prepared for detailed surveying at IPP systems, which can provide vital and timely information on household electricity consumption outside of the areas currently served by LEC. This is very useful, not only for under-served areas of Monrovia, but also for outlying urban and even rural areas, where electricity consumption data is exceedingly scarce.

- Finally, LEC is undertaking numerous grid extension efforts – some of which include demand surveying – and continuing the day-to-day record keeping as part of its regular billing and payment system. These efforts constitute a growing dataset that, as penetration rates increase, will be invaluable for increasingly accurate estimates of demand in Monrovia and elsewhere.

All of these new data sources, as well as updated information on geo-located demands, and updated costs for equipment and other items, should be included both in consideration of this plan as guide for local planners and policy-makers, as well as any planning efforts that build upon it in the future. The training efforts conducted as part of this TOR have familiarized local energy practitioners with the core skills used in this approach and prepared them to interpret these results with a basis of insight into the methods employed.

A related purpose of this master plan has been to create a framework to help guide donors and investors in an effort to electrify Liberia. In general, the report suggests a broad program with large investments over many years. Phasing and geographic county-by-county analysis provided in the report may help funders and planners to break the results into more practical tranches. Meanwhile, some contents of this report – such as the “half-capacity” stand-alone power system cost and technical estimates -- may suggest that can be the basis for specific, smaller projects that may represent opportunities for shorter-term implementation.

Appendix A

Table 15: Points of origin for grid expansion (includes urban centers as defined by LISGIS, cross-border extensions, and CLSG sub-stations).

Name	County	Population	Households
Bong Mines Municipal Grid	Bong	10,166	6,389
Buchanan Substation	Grand Bassa	54,245	6,479
Foya Town Municipal Grid	Lofa	20,569	11,722
Gbarnga Municipal Grid	Bong	43,713	15,289
Greenville Municipal Grid	Sinoe	13,370	3,052
Harbel Municipal Grid	Margibi	25,309	10,891
Harper / Côte d'Ivoire Cross Border	Maryland	23,517	5,730
Kakata Municipal Grid	Margibi	34,608	21,064
Kpayeakwe Municipal Grid	Gbarpolu	5,360	1,815
Kungbor Municipal Grid	Gbarpolu	8,141	2,195
Monrovia System	Montserrado	1,021,764	200,934
Suakoko Municipal Grid	Bong	9,797	6,500
Tubmanburg Municipal Grid	Bomi	14,576	30,027
Voinjama Municipal Grid	Lofa	15,569	8,870
Yekepa Substation / Guinea Cross Border	Nimba	7,176	3,620
Yogbo Municipal Grid	Bong	6,400	9,913
Ziah Town Municipal Grid	Grand Gedeh	9,253	2,790
Zorzor Municipal Grid	Lofa	5,577	8,531
Zwedru / Côte d'Ivoire Cross Border	Grand Gedeh	25,349	6,381
Mano Substation	Grand Cape Mount	<1,000	<200

Appendix B

Table 16: Comprehensive List of NetworkPlanner Optimization Tool Inputs, Metrics and key Assumptions

Category	**Metric**	**Value**
demand (household)	household Base unit demand per household per year [kWh]	300
demand (household)	target household penetration rate	70% Rural 100% Urban
demand (peak)	peak demand as fraction of nodal demand occurring during peak hours	40%
demand (peak)	peak electrical hours of operation per year	1460
demographics	mean household size (rural)	9.6
demographics	mean household size (urban)	7.5
demographics	mean inter-household distance [m]	15
demographics	population growth rate per year (rural)	1.5%
demographics	population growth rate per year (urban)	3.6%
demographics	urban population threshold	5000
distribution	low voltage line cost per meter	$40
distribution	low voltage line equipment cost per connection	$100.00
distribution	low voltage line equipment operations and maintenance cost as fraction of equipment cost	1%
distribution	low voltage line lifetime	30
distribution	low voltage line operations and maintenance cost per year as fraction of line cost	1.0%
finance	economic growth rate per year	3.73%
finance	elasticity of electricity demand	1
finance	interest rate per year	7%
finance	time horizon	30

Category	**Metric**	**Value**
system (grid)	available system capacities (transformer)	5-1000 kVA
system (grid)	distribution loss	12%
system (grid)	electricity cost per kilowatt-hour	**$0.15**
system (grid)	installation cost per connection	$25
system (grid)	medium voltage line cost per meter	$40
system (grid)	medium voltage line lifetime	30
system (grid)	medium voltage line operations and maintenance cost per year as fraction of line cost	1%
system (grid)	transformer cost per grid system kilowatt	$105
system (grid)	transformer lifetime	10
system (grid)	transformer operations and maintenance cost per year as fraction of transformer cost	3%

Category	Metric	Value
system (mini-grid)	available system capacities (diesel generator)	6 - 1,000 kW
system (mini-grid)	diesel fuel cost per liter	$1.20
system (mini-grid)	diesel fuel liters consumed per kilowatt-hour	0.4
system (mini-grid)	diesel generator cost per diesel system kilowatt	$150
system (mini-grid)	diesel generator hours of operation per year (minimum)	1460
system (mini-grid)	diesel generator installation cost as fraction of generator cost	25%
system (mini-grid)	diesel generator lifetime	5
system (mini-grid)	diesel generator operations and maintenance cost per year as fraction of generator cost	10%
system (mini-grid)	distribution loss	10%

Category	Metric	Value
system (off-grid)	available system capacities (photovoltaic panel)	50-1,500 kW
system (off-grid)	diesel generator hours of operation per year (minimum)	1460
system (off-grid)	peak sun hours per year	1640
system (off-grid)	photovoltaic balance cost as fraction of panel cost	50%
system (off-grid)	photovoltaic balance lifetime	10
system (off-grid)	photovoltaic battery cost per kilowatt-hour	$213
system (off-grid)	photovoltaic battery kilowatt-hours per photovoltaic component kilowatt [$/V•Ah]	7
system (off-grid)	photovoltaic battery lifetime	2.5
system (off-grid)	photovoltaic component efficiency loss	10%
system (off-grid)	photovoltaic component operations and maintenance cost per year as fraction of component cost	5%
system (off-grid)	photovoltaic panel cost per photovoltaic component kilowatt	$1,000
system (off-grid)	photovoltaic panel lifetime	20