Improving Electricity Access and Reliability using Residential Solar Systems with Battery Storage Systems in Sub-Saharan Africa

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Abstract

Poor access and unreliable grid service are amongst the significant challenges facing households in sub-Saharan Africa. In response, these households rely on fossil fuel-based technologies to meet their household needs. Families without grid access rely on kerosene lamps predominantly to meet lighting needs, while grid-connected homes use fossil fuel backup generators. Studies of fossil fuel solutions like kerosene lamps and backup generators show that these technologies impose negative socio-economic impacts on both households and society. As a result, researchers and policymakers have been motivated to explore cleaner and more sustainable technologies like residential solar electric with battery storage systems. This thesis through a quantitative investigation of residential solar systems to analyzes the technical, economic, and environmental merits of residential solar systems in their applicability to address key electricity challenges facing sub-Saharan households.

For households in rural areas without access in Kenya, solar home systems provide a cost-effective alternative to kerosene lamps as a better lighting alternative, and even better for household economics when the additional services are considered like phone charging.
I found was price elasticity of demand to be the key determinant of economic attractiveness for lighting services, which attempts to quantify the value households place on improved lighting service.

For grid connected households, findings suggest that residential solar with battery storage electric systems can provide improved household electricity reliability while reducing reliance on backup generators. However, these systems increase grid demand. The main driver of the economic attractiveness of these systems are the household's reliability needs which is reflected in how many hours the household's backup generators is available for dispatch in the event of a grid outage as well as discount rate. The study finds that grid availability is also a key determinant of the economic attractiveness of these residential systems, because the quality of grid service in terms of how many hours the grid provides power to the household determines the overall level of backup generator reliance.

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1 Introduction

The promise of economic development driven by reliable and affordable electricity service remains elusive for over 600 million Sub-Saharan Africans, primarily rural dwellers who do not have access to clean and reliable sources of energy[1]. Grid extension has long been the traditional approach adopted by policymakers to provide electricity services to rural unconnected households[2]—an approach which has failed to deliver in providing access to reliable electricity services to households and businesses in majority of sub-Saharan countries[2], [3]. Households without access to the grid therefore have no choice but to use dirty, and inefficient fuel sources to meet their household needs [3]–[7] These disadvantaged communities rely on inefficient and dangerous fuels for their lighting and cooking needs. For lighting needs, households predominantly rely on kerosene lamps[4]. Studies have shown that the high prevalence of kerosene use imposes significant negative burdens on families and communities[8]. Poor quality lighting from kerosene lamps increases the exposure of household members to indoor air pollution, burns, and unintentional ingestion among children and adults. These consequences primarily affect women and children, who spend more time in the home[9]. Use of kerosene lamps increases the risk of fires and explosions. Combustion of kerosene also contributes to greenhouse emissions[10].

Even when a grid connection is made, majority of households still suffer from frequent interruptions of long outage duration [11]–[13]. One response is to return to kerosene lamps which therefore erodes all the benefits the grid connection is supposed to accrue to the households[3]. Other households invest in fossil based backup generators. For example, 80% of grid-connected households in Nigeria employ fossil fuel based backup generators to combat unreliable service [14]. Operating backup generators is economically burdensome to as it reportedly consumes between 15- 40% of a household's income [15], [16]. Other externalities from backup generator use reported in the literature include noise pollution, air pollution, and increased mortality rates [13], [17], [18]

Recognizing the significant challenges to the central grid as means to provide electricity service to unconnected communities, scholars and policymakers have explored off grid alternatives like mini-grids (micro-grids), and stand-alone technologies like solar-powered lamps (solar lanterns) and solar home systems (SHS)[2], [19]–[21]. These alternatives are often smaller, scalable and powered via renewable sources like solar, thus providing opportunities for countries to sustainably provide electricity service. Sub-Saharan countries can leapfrog outage centralized grid expansion approaches to provide electricity service with large populations of unconnected households.

In this dissertation, I primarily focus on residential solar systems which are integrated systems that include photovoltaic (PV) cells, battery storage, controller units, and, in some cases, consumer appliances [22] and come in different sizes to cater to a wide range of electricity needs of household. The aim of the dissertation is to perform a techno-economic assessment of residential solar systems as a tool for households and policymakers in Sub-Saharan countries to combat the challenges of poor access and unreliable service for grid connected households.

Chapter 2 and Chapter 3 examine from a household's perspectives, the economic feasibility of these systems in addressing two distinct energy challenges facing Sub-Saharan African households. In Chapter 2, I use load and household expenditure data from households without grid access to perform a data driven cost benefit analysis of Solar Home Systems in Kenya. In Chapter 3, I explore the economic feasibility of integrating residential solar systems with battery storage to improve household reliability in households experiencing poor grid service in Nigeria. I use data from the End-Use Metering survey of selected households in six states in Nigeria (Lagos, Abuja, Bauchi, Edo, Sokoto, and Enugu). In Chapter 4, I assess the emissions savings potential of these systems, using the technical output results from Chapter 3. Chapter 5 concludes the dissertation with a discussion of the implications of this work as well as recommendations for future work.

2 An Economic Analysis of Replacing Kerosene Lamps with Solar Options in Kenya using Household Load Data

2.1 Introduction

In this chapter, I conduct a benefit-cost analysis, from a private user perspective, of replacing kerosene lamps with standalone solar options in Kenya based on measured load data. Costs include the costs of purchasing or leasing the solar system. The benefits included are based on a consumer surplus model that quantifies the benefits of improved lighting services (higher lumen-hours as well as the difference in the operating costs to provide such lumen-hours). In addition, the benefits account for avoided expenditures on other services such as phone charging and entertainment provided specifically by the SHS. Unlike prior work, I use measured system performance and use patterns in this analysis.

2.2 Data Sources and Methods

In order to evaluate the benefits of switching to stand-alone solar systems, I needed to estimate the demand for lighting before and after the connection of the system. To estimate demand prior to connection, I relied on customer-reported demand for kerosene. Lighting demand after the connection of the system is based on measured load data for customers from a leading SHS provider operating in Kenya. In particular, I obtained data for 1,151 unique SHS customers in Homa Bay County. The data included each customer's monthly expenditure on kerosene (assumed to be used exclusively for lighting), phone charging, and batteries (assumed to be used for radios) prior to obtaining the SHSs, as well as measured load data after system installation. All these customers purchased 15W systems, which came with a 15W rooftop solar panel, a battery system, four (1W) LED lights, a radio (4W), and a phone charging dock (3W). The full cost of the 15W systems was $350, but customers could lease the systems from the SHS provider for three years and assume full ownership once the lease was completed. The lease included an upfront payment of $11 and 35 monthly installments of approximately $9.5 ($114 annually). I have assumed that customers only used the appliances provided by the SHS provider, as the systems are not designed to allow the connection of non-provider appliances. I also assumed an upfront cost for solar lanterns to be $20/lantern (D-Lab, 2015) in order to compare such option to lighting provided by the SHS.

2.2.1 Estimating demand for kerosene-based lighting

For this paper, I estimated the lighting produced by kerosene based on customer survey data. According to Ngugi (2013), 73% of households in Homa Bay County used simple wick kerosene lamps to provide lighting in 2013. Using the reported kerosene expenditures from SHS customers and the operating characteristics of a simple wick kerosene lamp (burn rate and luminous flux from [24]), I estimated the amount of kerosene lighting produced before connection of the solar system using

$$q_{kero} = (k/b) \times l_{kero} \tag{2-1}$$

where q_{kero} is the kerosene lamp light output in kilo-lumen-hour (klmh), k is the reported monthly kerosene consumption (in liters), b is the burn rate of the simple wick lamp (in liters per hour), and l_{kero} is the luminous flux of the simple wick lamp (in kilo-lumen, klm).

2.2.2 Estimating demand for solar lighting

To estimate lighting demand from the solar systems, I relied on empirical load data from the SHS provider. The data included timestamped voltage and net current readings from each customer's battery. The net current is the aggregate difference between the current from the solar generator less the current flowing to the loads. Negative net current readings mean that the charging current (battery charging) was greater than discharging (appliance use). Such negative net currents can only occur during daytime, when the sun is shining. Because accurately separating the operation of the charge controller and the appliance components from the current signal during charging (daytime) was challenging with the available data, I limited the analysis to nighttime use (19:00 – 05:59). Presumably, this is also the time when customers most need artificial light.

Fig. 2-1 Sample two-day time series of a SHS user's load. This study only used night-time data, shown between the red dashed lines (18:00-05:59)Fig. 2-1 shows a sample two-day time series of the customer load data from the SHS provider. The raw dataset included 65,665 days of load data across 1,151 customers, spanning from January 2014 to the end of September 2015. I removed observations (days) from the dataset based on: 1) days on record before the customer signed their lease for that system; 2) observations that had current and/or voltage readings outside of operational limits (see 6); 3) observations that reported charging during nighttime hours. After data processing, 33,319 days of customer load data remained. Using these load data, I then estimated the number of lamps used during night-time by disaggregating the load data into a daily lamp use profile. The resultant profile was converted to a monthly demand for solar lighting, in klmh, for each customer.

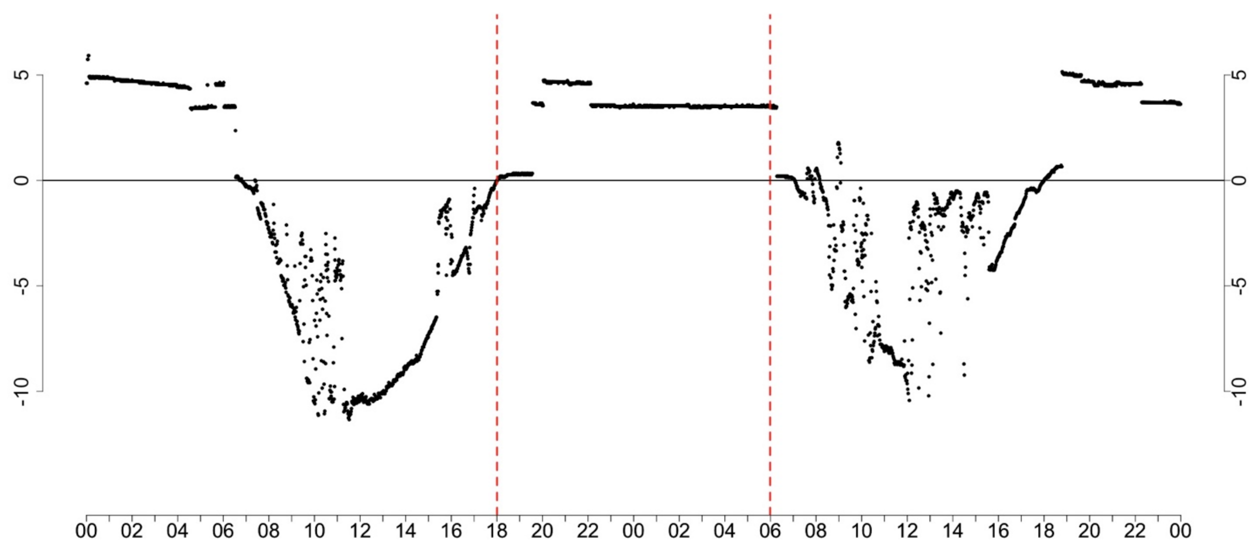

Fig. 2-1 Sample two-day time series of a SHS user's load. This study only used night-time data, shown between the red dashed lines (18:00-05:59)

Unfortunately, I was not provided with ground truth data about the measured power consumption of each appliance to complement the customer load data, so validation of the results was not directly possible. I decomposed the actual load data into the appliance use states based on the average power consumption of the appliances provided by the SHS provider (four 1W lamps, a 4W radio and a 3.8W phone charging dock), which resulted in 18 relatively distinct load states. Each load observation was classified into a given state by selecting the highest load state, in Watts, lower than the load reading. This heuristic prevents our disaggregation algorithm from attributing higher consumption than the actual readings. Though the average power consumption of each device is relatively distinct, it is easy to see that if the appliances are used together the total power consumption cannot always be accurately disambiguated. For example, a total consumption of 7.8 W could be attributed to four lamps and phone charging. Alternatively, that load could be from a radio and phone charging. Table 2-1 shows a matrix of appliance use for all possible load states. I found that 7% of the load observations[1] were either 4 or 7.8W. In each of these cases, there are two possible appliance-use scenarios, as described in Table 1. For the rest of the analysis, I used the scenario with the higher lamp use (denoted as S1 in Table 2-1).

Table 2-1: Appliances in use for different load sates.

Available Appliances	**Load State (Watts)**																			
	0	**1**	**2**	**3**	**3.8**	**4**		**4.8**	**5**	**5.8**	**6**	**6.8**	**7**	**7.8**		**8**	**8.8**	**9.8**	**10.8**	**11.8**
						S1	**S2**							**S1**	**S2**					
Phone Charger					x			x		x				x	x		x	x	x	x
Radio							x		x			x	x		x	x	x	x	x	x
Lamp 1		x	x	x		x		x	x	x		x	x	x		x	x	x	x	x
Lamp 2			x	x		x				x		x	x	x		x		x	x	x
Lamp 3				x		x							x	x		x			x	x
Lamp 4						x								x		x				x

To evaluate the option of using solar lanterns instead of a SHS, I assumed such lanterns would provide the same lamp-hours as the light bulbs from the SHS, as estimated for each customer through the above-mentioned load disaggregation process. While our data include information for 1,151 SHS customers, the number of night-time observations varies across customers. Variations in number of nighttime observations resulted from differences in time of purchase of the SHS (i.e. some customers may have purchased the systems in January 2014 and have observations until September 2015, while other customers may have purchased the system in December 2014, so they only have 9 months of observations). Furthermore, I removed some observations during data processing (as previously described).

To better incorporate the variance that results from the smaller samples across customers, I fit a linear regression model for each lamp-use scenario as shown in Eq. (2-2):

[1] See (Table A- 1 and Fig. A- 3 in Appendix)

$$Lh_c = \beta_c + e_c \tag{2-2}$$

where Lh_c is daily lamp-hours estimated for a customer c using all observations for that customer; β_c is the individual customer lighting effect, and e_c is the error term.

I estimated the 95% confidence interval for each customer's average daily lamp-hours allowing a fixed correlation of the errors within each household but independence across households (i.e., the variance-covariance matrix of the errors is compound symmetric). Finally, I used each customer's daily lighting estimate, Lh_c, to calculate the monthly synthetic light output from a given solar technology (SHS lamps or solar lanterns), in klmh, as shown in (2-3):

$$q_{SC} = (Lh_c) \times l_S \times 30 \tag{2-3}$$

where q_S is monthly lumen-hours used by customer c; Lh_c is the daily lamp-hours estimated for customer c; and l_S, is the luminous flux of either the SHS lamps (0.128klm) or the solar lanterns (0.05klm).

2.2.3 Estimating Benefits from Solar Technologies

Solar lighting options benefit consumers by providing improved lighting, and in the case of SHS, by providing cell phone charging and entertainment benefits. Previous studies suggest increased luminosity from LED light bulbs in SHS or solar lanterns is a key benefit of replacing kerosene lamps [25]–[27]. To quantify this (non-monetary) benefit, I relied on a consumer surplus model previously used by the World Bank [28] and other researchers [3], [29]. Consumer surplus is based on a demand function that models the relationship between the demand of a commodity/service – in our case lighting units (klmh) –and the price paid for said commodity/service. Specifically, I relied on a demand model developed for kerosene lamps based on customer's willingness to pay and a constant elasticity of demand. I further assumed this function to be applicable to the demand for solar lighting as shown in Eq. (2-4):

$$p(q) = \left[\frac{A}{q}\right]^{\frac{1}{\varepsilon}} \tag{2-4}$$

where $p(q)$ is the price the customer is willing to pay for consuming q units of lighting in $/klmh; A is a constant; and ε is the price elasticity of demand. The elasticity of demand for lighting energy services by rural customers in developing countries is poorly understood, so I modeled it parametrically through a sensitivity analysis. Based on electrification studies in developing countries, I found that the elasticity of demand for energy services is typically inelastic (<1), therefore I selected a lower (0.2) and upper (0.8) elasticity values found in the literature [3], [28], [29]. Consequently, using the price paid, in $/klmh, and the light output from the kerosene (as reported in the data obtained from the SHS provider) I created two separate demand functions using the different elasticity values for each customer (See Fig. A- 4). For a given demand function, I then estimated the consumer surplus as the difference between the area under the demand curve at point q, and the total expenditure of consuming q units of lighting at price p(q), as described in by Eq. (2-5):

$$CS = \left[\int_0^q p(q)dq\right] - [p(q) \cdot q] \tag{2-5}$$

where CS is the consumer surplus; q is the amount of the lighting units consumed (in klmh); p(q) is the price paid for consuming q (in $/klmh).

Our analysis assumes that prior to installing the systems, customers used kerosene lamps to meet lighting needs so that the change in consumer surplus associated with replacing kerosene lamps with solar lighting is defined with Eq. (2-6):

$$NetCS_S = \left[\left[\int_0^{q_s} p(q)dq\right] - (p(q_s) \cdot q_s)\right] - \left[\left[\int_0^{q_{kero}} p(q)dq\right] - (p(q_{kero}) \cdot q_{kero})\right] \tag{2-6}$$

where $NetCS_S$ is the net consumer surplus of replacing kerosene lighting with solar lighting (either SHS or solar lanterns); $q_s$and q_{kero} represent the light output from solar and kerosene lighting respectively, in klmh; p(q) is the price paid for consuming q, in $/klmh. For this analysis, I assumed that $(p(q_{kero}) \cdot q_{kero})$ is the monthly expenditure on kerosene ($MonthEx_{kero}$) reported by the customers when signing up for the SHS. The marginal price of solar lights, $p(q_s)$, is zero as the only cost associated with these lamps is the initial purchasing cost (or the monthly leasing fee) and operating the lamps is free as long the sun shines to charge the batteries. As a result, (2-6) becomes Eq. (2-7)

$$NetCS_S = \left[\int_{q_{KERO}}^{q_S} p(q)dq\right] + MonthEx_{kero} \quad (2\text{-}7)$$

I note that while this consumer surplus analysis does not include the costs of purchasing (leasing) the solar systems, I account for these costs in the benefit cost ratio calculation described later in this paper. Finally, the SHS provides a dock for phone charging and a radio so I assumed the expenditures on phone charging (pc) and batteries (b) the customers reported in their applications to the SHS provider would be avoided. I categorized the avoided expenditure as a benefit accrued to the customer as defined in Eq. (2-8):

$$AS_c = \sum_{i=\{pc,b\}} C_{i,c} \cdot f_{i,c} \quad (2\text{-}8)$$

where AS is additional services ($US) for customer c, i is the service provided, c_i is the cost of service prior to the SHS connection (US$), and f_i is the frequency of the service used per month as reported by c.

The total benefits from a given solar lighting technology, s, is then the sum of the change in consumer surplus and the avoided expenditures on cell phone charging and radio, as defined in Eq. (2-9)

$$B_{SC}(\varepsilon) = (NetCS_{SC}(\varepsilon) + AS_{SC}) \times 12 \quad (2\text{-}9)$$

where B_{SC} is the full annual benefits (US$) estimated for customer c for a given solar technology s; $NetCS_{SC}(\varepsilon)$ is the monthly consumer surplus (US$), which depends on the price elasticity selected, ε; and AS_{SC} is the monthly benefits from additional services (US$). The solar lanterns I considered provided only lighting benefits.

2.2.4 Benefit Cost Ratio of Solar Options

Using the costs of the solar options and the annual benefits previously calculated, I performed a benefit cost ratio analysis to evaluate the economic attractiveness of replacing kerosene. Based on the typical life of a SHS, I use a 5-year time horizon, starting at year 0 and ending in year 4, to discount future costs and benefits to their present value. As per the lease agreement of the SHS provider, the initial cost of the SHS in year 0 is US$115.5 and there are two additional payments of US$114 in years 1 and 2 (there are no payments for these systems in years 3 and 4). For solar lanterns, I assumed a life time of 2 years (D-Lab, 2015), which implies that the lanterns need to be replaced twice (at years 2 and 4) after the initial purchase in year 0. Therefore, the benefit cost ratio for the solar options for each household is given by Eq. (2-10):

$$BCR_{SC}(\varepsilon, i) = \frac{\sum_{t=0}^{4} \frac{B_{SC}(\varepsilon)}{(1+i)^t}}{\sum_{t=0}^{2} \frac{C_S}{(1+i)^t}} \tag{2-10}$$

where BCR_{SC} is the benefit cost ratio of solar option s (SHS or lantern) for customer c; $B_{s,c}$ are the benefits of solar option s accrued to customer c, which depends on the price elasticity ε; C_s is the annual cost of the solar system, i is the discount rate, and t is the year. A BCR higher than one suggests that the benefits of replacing kerosene with solar options are higher than the costs of the solar systems, hence they are economically attractive. Just like the price elasticity, I modelled the discount rate parametrically through a sensitivity analysis. The discount rates selected were: 5%, 15% and 25% based on the values found in similar studies [3], [28], [29].

2.3 Results

Fig. 2-2 shows the result of the disaggregation for a single nighttime observation. The black points show the actual power consumption, the red line indicates the number of lamps used at the given time in a high lamp use scenario (S1 in Table 2-1), and the green dashed line indicates the number of lamps used in a low lamp use scenario (S2 in Table 2-1). In our high lamp use scenario, between 20:00 and 22:00, this customer used 4 lamps (0 lamps in the low lamp use scenario).

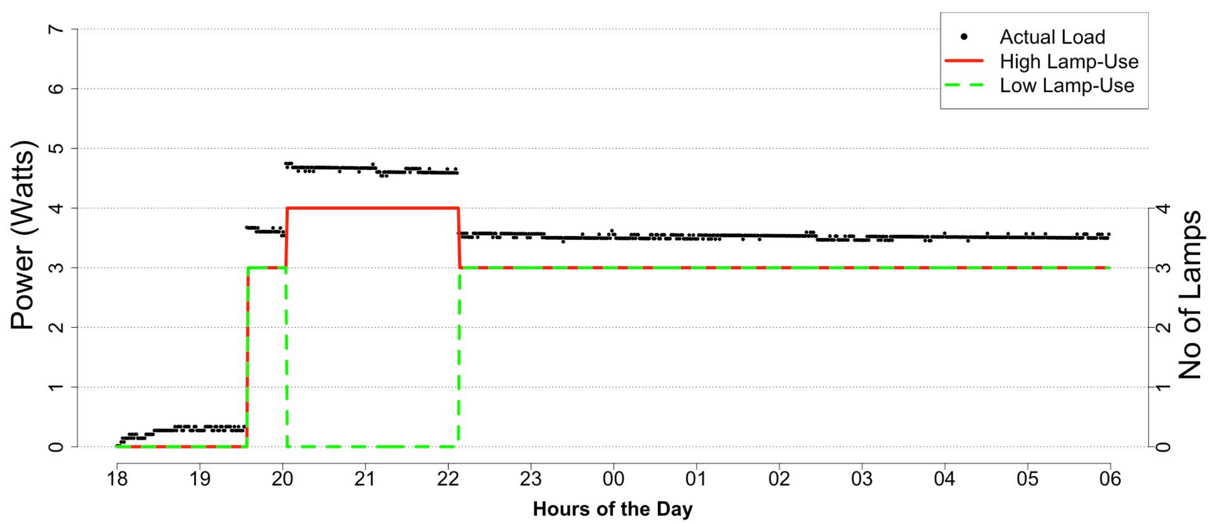

Fig. 2-2 Disaggregation results (in red) for a sample night-time customer load profile

Based on, 815 of the 1,151 customers analyzed had lamp-use estimates (in lamp-hours) that were statistically different from zero. Therefore, the results in this paper focus on the data for those 815 customers. Fig. 2-3a shows the distribution of system lamp-use estimates among these customers. These customers used on average 12.3 lamp-hours per night (95th confidence interval (CI): 4.7, 27.1 lamps-hours).

Prior to installing the SHS, I estimated that the average monthly kerosene light output for these customers was 4.8 klmh (95th CI: 0.78, 15.6 klmh), as shown in Fig 3b. I estimated the average monthly light output from the SHS to be 47.4 klmh (95thCI: 18.1, 104.1 klmh), and from the solar lanterns 17.4 klmh (95thCI: 6.6, 38 klmh). The differences in light output I observe in both scenarios between the solar options was as a result of the difference in luminosity—the lamps from the SHS provide approximately three times the luminosity of the solar lanterns. The average output from the SHS and Solar lanterns exceeded the output from the kerosene lamp in the high scenario by a factor of 18 and 7, respectively.

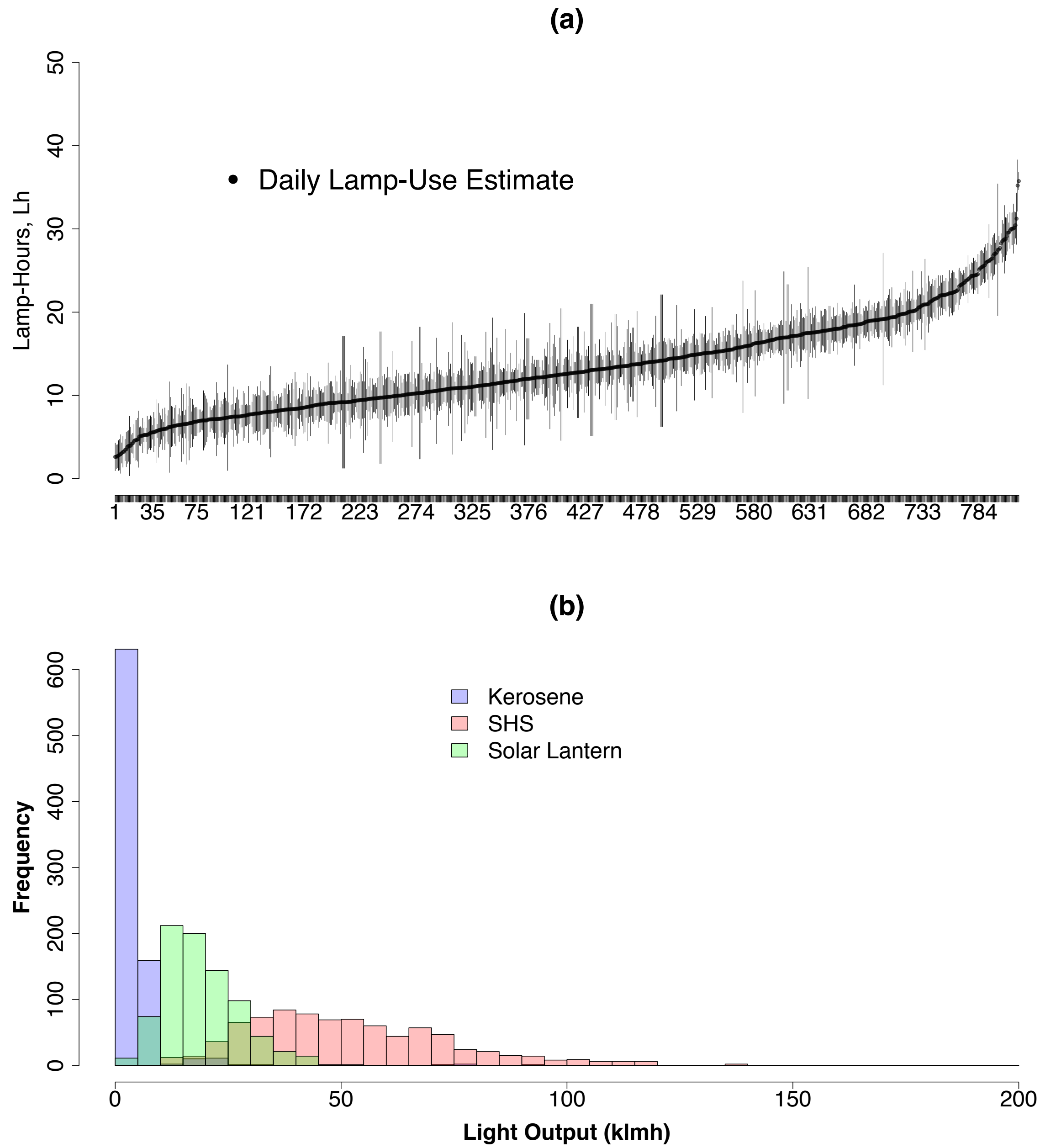

Fig. 2-3 Regression results for daily lamp use sorted in ascending order (top); histogram of monthly average lighting output from lighting options (bottom).

2.3.1 Estimated Annual Benefits from Solar Technologies

Fig. 2-4 illustrates the annual benefits for each solar technology considered to replace kerosene lamps. For SHS, I illustrate the distribution of lighting benefits only (net consumer surplus) in Fig. 2-4a. The median annual net consumer surplus was: US$57 for ($\varepsilon = 0.2$) and US$126 ($\varepsilon = 0.8$). Fig. 2-4b illustrates the distribution of SHS with the full benefits considered and shows the median to be: US$70 for ($\varepsilon = 0.2$) and US$143 for ($\varepsilon = 0.8$). For Solar lanterns, I illustrate the distribution of benefits (lighting only) in Fig. 2-4c. The median annual benefits of solar lanterns were: US$56 for ($\varepsilon = 0.2$) and US$98 for ($\varepsilon = 0.8$). I also compared differences in net consumer surplus between the solar options in Fig. 2-4d. These figures suggest that the difference, despite the SHS lamps providing three times the luminosity, was negligible, particularly for customers with low elasticity of demand ($\varepsilon = 0.2$) for whom the median difference in benefits was 0. However, at a higher elasticity value, ($\varepsilon = 0.8$), the differences in benefits between the solar lanterns and the SHS increased, which suggests that customers with higher elasticity would place greater value on improved quality lighting. Furthermore, when additional services of the SHS are considered, the median difference in benefits between the SHS and the solar lanterns range from $12 to $42 annually (not shown).

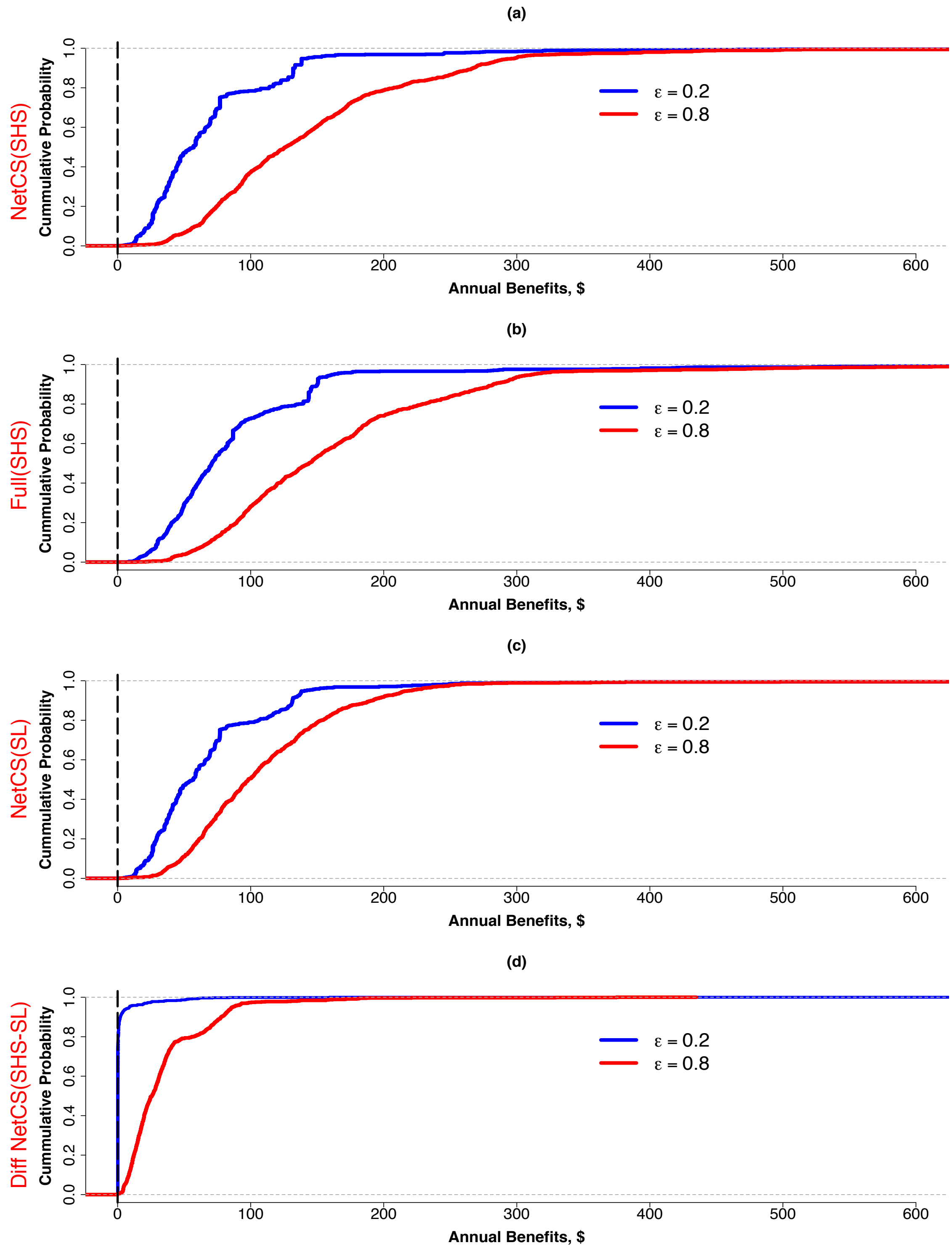

Fig. 2-4 Annual benefits in US$/year for: a) Net Consumer Surplus for SHS; b) Full Services SHS ; c) Net Consumer Surplus Solar Lanterns; d) Difference between Net Consumer Surplus for SHS and solar lanterns.

2.3.2 Benefit Cost Ratios (BCR) for Solar Technologies

While Fig. 4 highlight differences in benefits between solar lanterns and SHS, the costs of these lighting options are significantly different, which affects their attractiveness as replacement for kerosene lamps. I use a BCR to account for such costs and compare the attractiveness of these systems. A BCR larger than one suggests that the benefits of lamp replacement are higher than the costs of the solar-based systems. Fig. 2-5 shows the results of the BCR for both solar options for all considered price elasticity values and a 15% discount rate. For the SHS (Fig. 2-5a), the median BCR for customer with low elasticity ($\varepsilon = 0.2$) was 1.0. This suggests 50% of these customers would not recover the costs of the SHS. However, if their demand elasticity increases ($\varepsilon = 0.8$), the median BCR for the customers in our database increases to 2.1. Under this high-elasticity scenario, only 10% of customers would have a BCR lower than 1 and would not recover the costs of the SHS.

For solar lanterns (Fig. 2-5b), the median BCR was 1.3 for the low elasticity scenario ($\varepsilon = 0.2$) and 2.3 for the high elasticity scenario ($\varepsilon = 0.8$). The percentage of customers with BCRs greater than 1 for the solar lanterns was 62% for the low elasticity scenario ($\varepsilon = 0.2$) and 93% for the high elasticity scenario ($\varepsilon = 0.8$). Finally, I found that these results did not change significantly when I used the low lamp-use scenario (Table A- 2) or different discount rates, as shown Table A- 3in the Appendix.

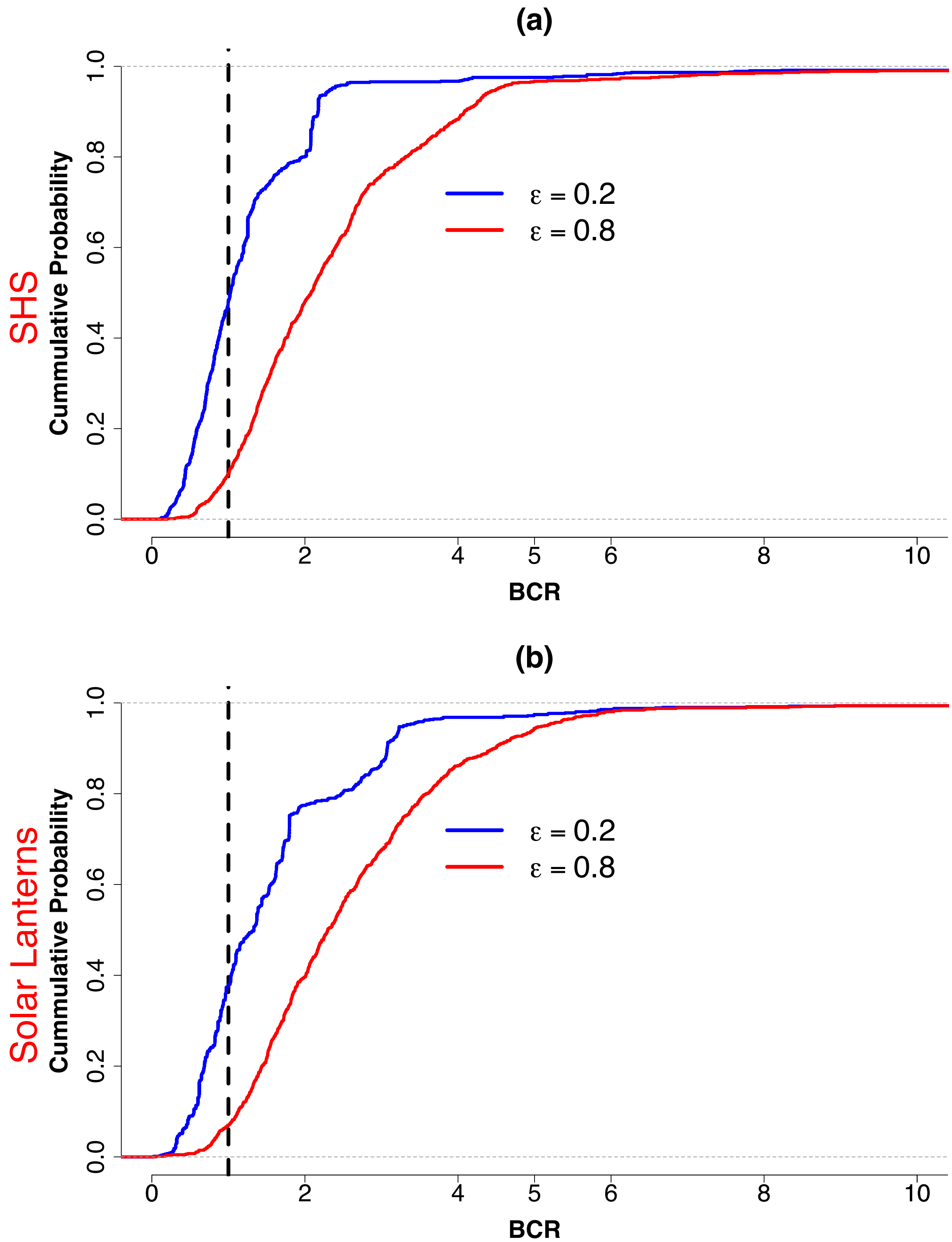

Fig. 2-5 Benefit Cost Ratios for SHS (a) and Solar Lanterns(b); Lower and Upper Bound in black and orange lines respectively

2.4 Discussion

In this study, I relied on empirical load data from SHS customers in Kenya. Such empirical data suggests that lighting use can vary from time to time and among customers, which contradicts the assumption of fixed lighting use in previous work. Our results show, however, that customers with solar lighting typically have higher demand for lighting services (measured in lumen-hours) compared to their kerosene lighting demand prior to the solar system installation. These findings align with previous research showing that solar lighting allows users avoid the cost of kerosene [3], [6], [30].

A key driver of the attractiveness of solar lighting as replacement for kerosene lamps is the elasticity of demand. This elasticity of demand is a measure of the value customers assign to lighting services. If customers have low demand elasticities, solar lighting options may not be cost-effective as replacement for kerosene lighting. Such customers may also find solar lanterns have higher benefit cost ratios than solar home systems. The elasticity of demand for lighting in rural communities in Africa is not well-understood, so future work is needed to better quantify such elasticity. Since all the customers in our database have already purchased solar home systems, I can infer that these customers have higher values for the elasticity of demand. As a result, solar lighting options provide significantly more benefits than the costs of purchasing and operating the solar systems, as demonstrated by the benefit cost ratios I previously reported.

While I improve on prior work by using empirical demand data and performing detailed sensitivity analyses, there are some limitations to our work that merit special attention. First, the net consumer surplus model I used relies on the elasticity of demand parameter. Not only is this parameter highly uncertain, but it assumes a unit of lighting output, measured in klmh, is unique. However, this may not be the case and a customer may value differently a technology that provides 2 klm for one hour (2 klmh) and one that provides 1 klm for two hours (2 klmh). Second, the elasticity of demand assumes that "all lumens are created equal," and ignores other dimensions of lighting quality, such as color, that may influence customers choices and valuations on lighting [31].

Our work is also limited by the quality of the load data. Since disaggregated load data at the appliance-level was not available, I developed a disaggregation heuristic to estimate the number of lamps each customer used during the period data were collected. This disaggregation process adds uncertainty to our estimates of lighting demand. Furthermore, the available data used for this analysis did not permit broader evaluations of other private co-benefits that result from improved lighting services. Such co-benefits likely include time savings, improved health, and increased education activities. Therefore, our estimates may be a conservative valuation of the household benefits of solar technologies. These results suggest that even without these co-benefits, solar lighting options already provide direct benefits that exceed the costs of the systems.

While this analysis only considers the private benefits of the solar technologies, it is important to highlight the broader policy implications. For instance, providing solar technologies to replace kerosene could contribute significantly to Kenya's emissions reductions established in the Intended Nationally Determined Contribution (INDC) [32] committed in the Paris Agreements. Under these INDC, emissions should decrease by 30% relative to a business as usual scenario of 143 $MtCO_2eq$ in 2030. Using the median reported kerosene demand among the SHS customers (48 liters per year) and an emissions factor of 2.6 kg CO_2/liter [33], I estimate that at least 125 kg CO_2 per customer per year could be avoided. Extrapolating to the population of people without access to electricity in Kenya (35 million [34]), at least 4.4 Mt CO_2 per year could be avoided by replacing kerosene with solar technologies.

While the private –and social benefits—of solar lighting systems are evident, barriers still exist to achieve greater adoption of solar lighting technologies in Kenya. For example, the upfront and monthly costs of these systems can be too high for the poorest population. Structured financial facilities in the form of microfinancing could help mitigate this barriers [3], [35]. Providing better access to financial services through rural banking in India, for example, has shown the potential for improved adoption and market viability of SHS [29], [36]. Unrealistic expectations on the level of energy services solar lanterns and SHS can provide could also lead to user dissatisfaction with the systems [35]. Education campaigns that inform potential customers of best practices and the benefits of solar lanterns and SHS can ensure that these systems are deployed for the appropriate applications. Finally, this paper highlights that households that rely on kerosene for lighting can benefit from solar lanterns and SHS. While long-term economic development in Kenya and Sub-Saharan Africa will likely require a broader set of solutions that provide higher levels of electricity for productive uses, in the short term, stand-alone solar lighting systems can move the energy poor up the energy ladder.

3 An Economic Assessment of Residential Solar Electric Systems with Battery Storage in Lagos Households Experiencing Unreliable Grid Service

3.1 Introduction

According to the World Bank's Business survey, Nigerian businesses suffered the highest aggregate duration of outages [11]. Unreliable grid service forces Nigerian households to either go without electricity service or invest in backup generators[16][37][38]. Reliance on backup generators imposes significant welfare burdens on the household and negative externalities on society [13]. This chapter investigates the economic potential of residential solar electric systems with battery storage in Nigerian households experiencing unreliable grid service, as an alternative to fossil fuel backup generation only option. Existing studies of residential solar systems in Nigeria have primarily investigated these systems as standalone options for Nigerian households, which may not be how these systems are deployed. Household investing in these systems will operate them in conjunction with their existing electricity generating sources- grid supply and backup generation. Furthermore, these studies use financial metrics such as Levelized cost of energy (LCOE), which are not typically used by households to make capital budgeting decisions [39]. This chapter attempts to fill the gap in the literature by exploring the economic feasibility of the residential solar systems with battery storage in improving household electricity reliability while reducing reliance on backup generators. I use a discounted cash flow analysis to investigate, from a household's perspective, whether the potential savings generated from reduced reliance on backup generators expenditure economically justify investment in the residential solar electric systems with battery storage.

3.2 Techno-Economic Model Description

Our modeling framework consists of a technical model and an economic model, which are linked together to investigate the economic impacts of integrating the residential solar systems with battery storage on overall household electricity expenditure. I assumed a model horizon of 15 years.

3.2.1 Technical Model

For the generator modelling and dispatch, I relied on the multi-generator models used in the Stochastic Techno-Economic Microgrid Model (STEMM) [40]. I relied on similar mathematical formulations from STEMM to model the PV, diesel generators, inverters as well as battery storage. For PV, I used equations that estimate the PV module fill factor, which assumes that the PV array operates at the maximum power point (MPP). The battery storage model simulates the performance of a lead-acid battery bank using a modified version of the Kinetic Battery Model (KiBaM) [40], [41], and a capacity fade model to estimate the lifetime of the battery and the capacity degradation [42]. The technical model operates on an hourly resolution to capture the temporal overlaps between household load, grid and backup generator availability and meteorological inputs such as solar irradiation and ambient temperature. For example, household members may not be home when a grid outage occurs and therefore may not use their backup generators (in this case their household electricity needs goes unmet). The key technical outputs that feed into the economic model fuel and grid consumption, met and unmet household load, runtimes for backup generator and solar system components such as inverters and rectifiers.

3.2.1.1 Modelling Unreliable Grid Service

I adapted STEMM to include a grid supply module, since this is a key component of our analysis. Grid supply has been characterized as erratic and unpredictable by reports from households and the underlying distribution of the durations of grid supply is unknown [38]. Using this characterization, I model the household's grid supply as a single unreliable generator with stochastic durations of grid-service and grid-outages[43]. HOMER (Hybrid Optimization Model for Electric Renewables), a micropower optimization tool developed by NREL, similarly adopts this modelling assumption for grid unreliability[44]. This assumption comes with its shortcomings as it conflates all outages which can be planned i.e. scheduled maintenance practices, with unplanned outages which can be caused by mismatched grid demand and supply for instance, or infrastructure vandalism [45]. Unfortunately, households are not effectively informed prior to a planned outage and cannot plan for such events which in turn leads them to perceive all outages, including load shedding events as erratic and operate their residential energy systems accordingly. Another limitation is that it does not consider possible correlations of outages (and its durations) with time of day or seasons.

I created the hourly grid state matrix, **G**, over the model horizon using a two-state stochastic model to describe the availability of the grid in a given hour (i.e. whether the grid is on (G[h]=1) or the grid is off (G[h]=0)). The inputs required to model the grid schedule are the duration of a single grid service (T_{ON}), duration of a single outage (T_{OFF}), and an annual grid improvement factor (ω). The inclusion of an annual grid improvement factor extends the current state of modelling an unreliable grid service. I use an annual grid improvement factor of 1%.

Starting at year (y) , I converted the parameters summarizing the duration of grid service (T-ON) and grid outage (T-OFF) to rate parameters which determine exponential distributions defining the durations of grid service (λ_{ON})and grid outages (λ_{OFF}) shown in Eq. (3-1) and Eq. (3-2) respectively. For each subsequent year, I account for annual grid improvements by multiplying the grid service duration input by an exponential growth factor (ω) and the grid outage duration input by an exponential decay factor ($-\omega$).

$$\lambda_{ON}[y] = \frac{1}{(\mathrm{T_{ON}} \cdot e^{\omega(y)})} \tag{3-1}$$

$$\lambda_{OFF}[y] = \frac{1}{(\mathrm{T_{OFF}} \cdot e^{-\omega(y)})} \tag{3-2}$$

To determine the grid status before simulation, I first determined the a priori grid availability based on the two input grid parameters T_{OFF} and T_{ON} as shown in Eq. (3-3)

$$\mathrm{A} = \frac{\mathrm{T_{ON}}}{\mathrm{T_{ON}}+\mathrm{T_{OFF}}} \tag{3-3}$$

Next, I determined the status of the grid preceding the simulations using a uniformly distributed random variable U1 (U1~ Uniform (0,1) and following the condition presented in Eq. (3-4)

$$B = \begin{cases} 1, & \mathbf{U1} \leq A \\ 0, & \mathbf{U1} > A \end{cases} \quad (3\text{-}4)$$

If the grid is in the ON state, it remains in this state for a duration determined by sampling from an exponential distribution with the rate parameter as the inverse of the grid on duration, as shown in Eq.*(3-5)* before it switches to the OFF state

$$H_{ON} \sim \text{Exponential}(\lambda_{ON}[y]) \quad (3\text{-}5)$$

Similarly, if the grid is in the OFF State, it remains in this state for a duration determined by sampling from an exponential distribution with the rate parameter as the inverse of the grid on duration, as shown in Eq.*(3-6)* before it switches back to the ON state

$$H_{OFF} \sim \text{Exponential}(\lambda_{OFF}[y]) \quad (3\text{-}6)$$

This sequential process repeats itself until an hourly grid schedule over the model horizon is populated.

3.2.1.2 Dispatch

I also relied on the dispatch algorithm from STEMM to reflect unpredictable grid service. I also adapted the dispatch algorithm to include backup generator availability constraints since not all of the household's electricity needs not provided by the grid is met by dispatching the household's backup generator. For example, if an outage occurs when household members are not home, backup generators may not be used, and the load could go unmet. Our technical module includes an hourly binary state variable (r[h]) with an hourly resolution to indicate hours when the backup generator is available for dispatch. Based on the combination of grid status, backup generator availability and level of available solar, the dispatch determines the level of electricity ($Q_{X\text{-}Y}$) flowing from each of the electricity generating sources available denoted by the subscript (X). (Grid (G), Backup generator (D), Solar (PV), Battery storage (B); and Unmet (U)), to the either the household load (L) and(or) battery storage (B) destination denoted by the subscript (Y).

Table 3-1 Summary the dispatch algorithm for a given hour h.

Grid Status g[h]	Backup Status r[h]	Description	
0	0	Load goes unmet if PV and Battery Storage cannot meet load;	Fig. 3-1
0	1	Dispatch backup generators if PV and Battery Storage cannot meet load; Use PV to charge battery storage	Fig. 3-2
1	N/A	Use grid and PV to meet load and charge battery storage	Fig. 3-3

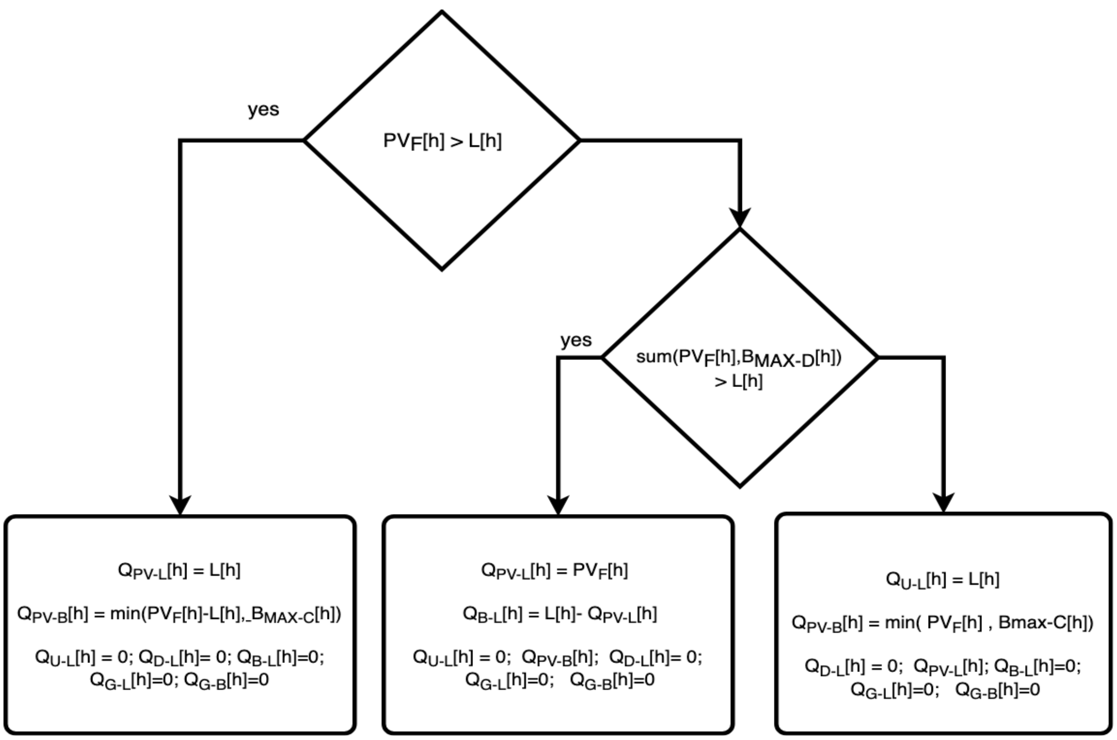

Fig. 3-1 Dispatch Flow Chart when the grid is OFF (g[h]=0) and the backup generator IS available for dispatch (r[h]=0)

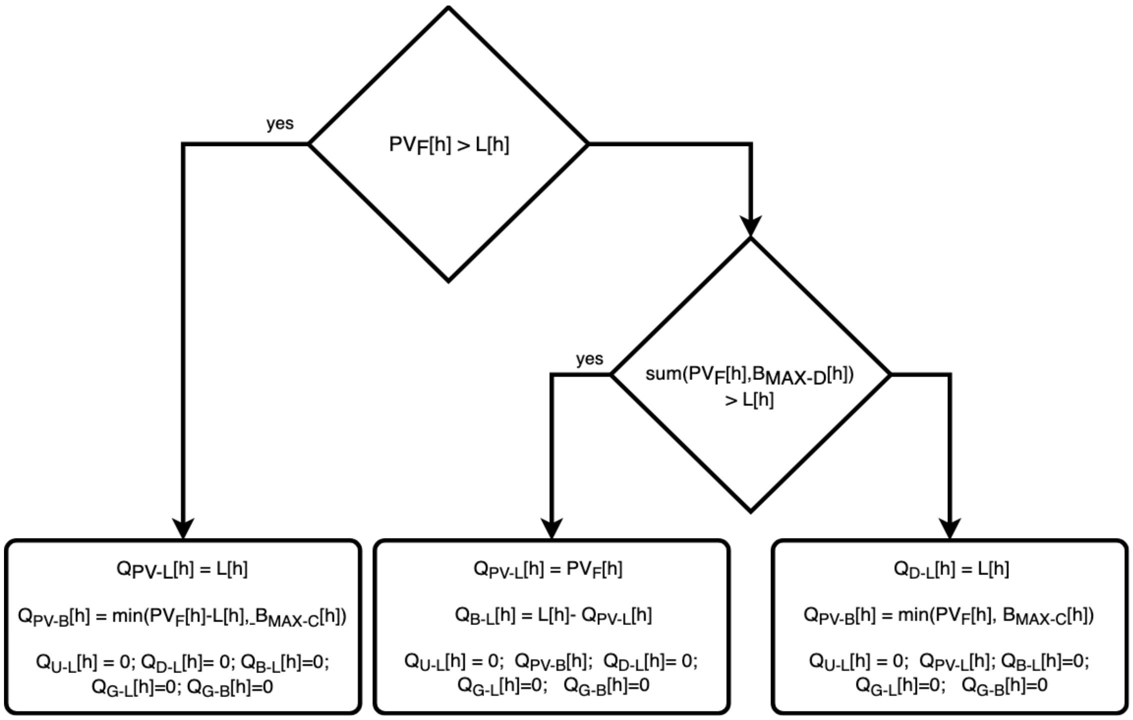

Fig. 3-2 Dispatch Flow Chart when the grid is OFF (g[h]=0) and the backup generator IS NOT available for dispatch (r[h]=1)

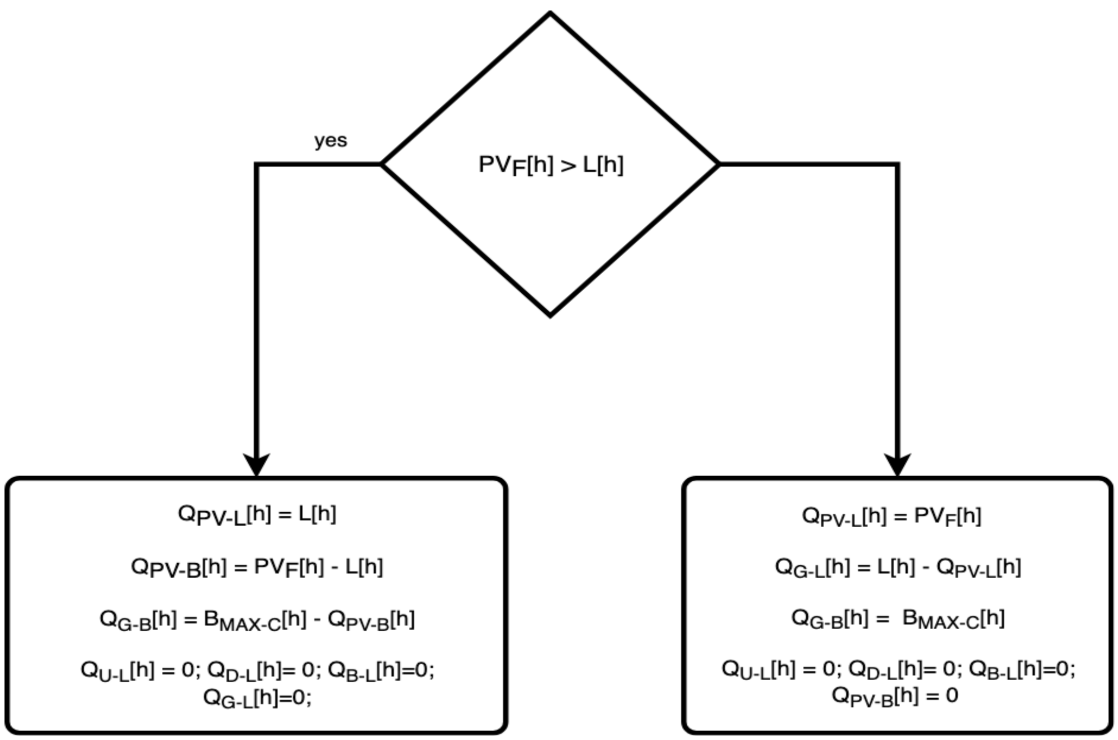

Fig. 3-3 Dispatch Flow Chart when the grid is ON (g[h]=1)

The constraints on hourly maximum levels of battery charging (B_{MAX-C}) and discharging (B_{MAX-D}) are determined by the ambient hourly temperature, and state of charge from the previous hour. In each hour the diesel generator is used, I estimated the fuel consumption from the level of electricity generated using Eq. (3-7)

$$\text{Fuel}_{D-L}[\text{h}] = (F_{NL} \cdot \text{Cap}_D) + \text{F}_L \cdot \text{Q}_{D-L}[\text{h}] \tag{3-7}$$

Where the intercept F_{NL}, is the no load fuel consumption which is consumed each time the generator is used regardless of amount of electricity generated; F_L, is the generator fuel slope or the marginal consumption in liters per kilowatt hour (l/kWh/hour); Q_{D-L} is the generator output at time h, and Cap_D is the installed capacity of the backup generator. I obtained the parameters or the no-load consumption parameter (0.0911), and for the marginal consumption parameter (0.264) [40]. I assumed a service lifetime of 15,000 hours and set the starting value of generator runtime tracker to half of the assumed service lifetime (7500) since I am analyzing households who already have backup generators. It is possible for the generator can be replaced multiple times within the model horizon depending on the frequency of use. In technology scenarios with battery storage, I adopted a capacity fade model to estimate battery lifetime and capacity degradation similarly used in [40], [42]. Once the battery storage capacity fade value falls below a maximum acceptable level of 0.2, the battery storage is replaced, I assumed that the inverters will be replaced every 12 years. Finally, I assumed a lifetime of 25 years for the solar PV modules, meaning that they are not replaced during the model horizon.

3.2.2 Economic Model

The primary output of the technical model that feeds into the economic model are grid consumption, fuel consumption, generator runtimes, battery capacity fade, and unmet load. The outputs considered in this paper are net present value of all associated costs (NPC), which is the sum of all discounted cashflows over the model horizon (15 years). I used the local currency in Nigeria (Naira, N) since all the associated costs incurred by the household are in local currency. The costs breakdown of each economic output is summarized in Eq. (3-8).

$$\begin{aligned} \mathrm{NPC} = {} & \delta_{Sys} \cdot IniCap + \sum_{y=1}^{15} \frac{\sum_{h=1}^{8760}(\mathrm{Q_{G-T}}[h,y]) \cdot g[y]}{(1+d)^y} + \sum_{y=1}^{15} \frac{\sum_{h=1}^{8760}(\mathrm{F_{D-L}}[h,y]) \cdot f \cdot (1+i)^y}{(1+d)^y} \\ & + \sum_{y=1}^{15} \frac{\sum_{h=1}^{8760}(D[h,y]) \cdot om \cdot (1+i)^y}{(1+d)^y} + \sum_{y=1}^{15} \frac{\mathrm{Repl_D}[y] \cdot \mathrm{CapEx_D} \cdot (1+i)^y}{(1+d)^y} \\ & + \delta_{Inv} \sum_{y=1}^{15} \frac{\mathrm{Repl_{Inv}}[y] \cdot \mathrm{CapEx_{Inv}} \cdot (1+i)^y}{(1+d)^y} \\ & + \delta_{B} \sum_{y=1}^{15} \frac{\mathrm{Repl_B}[y] \cdot \mathrm{CapEx_B} \cdot (1+i)^y}{(1+d)^y} + \sum_{y=1}^{15} \frac{\sum_{h=1}^{8760}(U[h,y]) \cdot g[y]}{(1+d)^y} \end{aligned} \tag{3-8}$$

where y is the year; h is the hour; d is the discount rate; δ_{Sys} is a dummy variable for Initial Capital cost of System (Ini.Cap);

Q_{G-T} is the total hourly grid consumed by the households (in cases with battery storage, include grid consumed for battery charging);

g[y] is the annual electricity tariff for year y;

F_{D-L} is the hourly fuel consumption from running backup generators;

f is the cost of fuel in (N/liter); i is the inflation rate;

D[h,y] is binary variable which indicates whether the generator is used;

om is the unit cost of operating and maintenance in Naira per use-hour (N/Diesel-Hour);

$Repl_D$ is a yearly binary variable which indicates the replacement year of the diesel generator;

$Repl_{INV}$ is a yearly binary variable which indicates the replacement year of the inverter;

$Repl_B$ is a yearly binary variable which indicates the replacement year of the battery storage;

Cap_B and Cap_{Inv} are the the capital cost of the battery storage and inverter respectively,
U is the hourly unmet load; and finally, δ_{Inv} & $\delta_B$are dummy variable for inverter or battery storage

In order to account for the improved electricity reliability that the residential solar systems provide, I considered an additional penalty for the cost of unmet load U[h, y] to the household. Each hour the household's load goes unmet, I assumed that the cost using the current grid tariff since our analysis assumes that the household would use the grid when available.

3.3 Data Sources and Model Inputs

My assumptions about hourly household electricity demand and grid service rely on data from the End-use Metering Campaign for Residential Houses [46]. This study selected a representative sample of over 200 households for participation on the basis of geographic and socio-economic characteristics in 5 states in Nigeria. Each household's total electricity consumption was measured using a series of watt-meters aggregated at the household's main circuit board on an hourly basis. For this chapter, I selected the results for Lagos since Lagos has the largest number of grid connected households and the largest electrification rate of 99% in Nigeria[47]. The report summarized the hourly load of 26 households in Lagos, and reported their hourly means during grid service. Fig. 3-4 illustrates the average hourly load profile for Lagos households summarized in the report.

The study also summarized the durations of grid service and outages measured and recorded using a series of watt-meters aggregated at the household's main circuit board. For the households in Lagos, the mean duration of a single grid outage was 4.4 hours (min:1.5 and max:15), and the mean duration of grid service when available was 6.3 hours (min:3 and max:12) [46]. I used the mean values of grid outages (T_{OFF}) and grid service (T_{ON}) to generate the base grid schedule used.

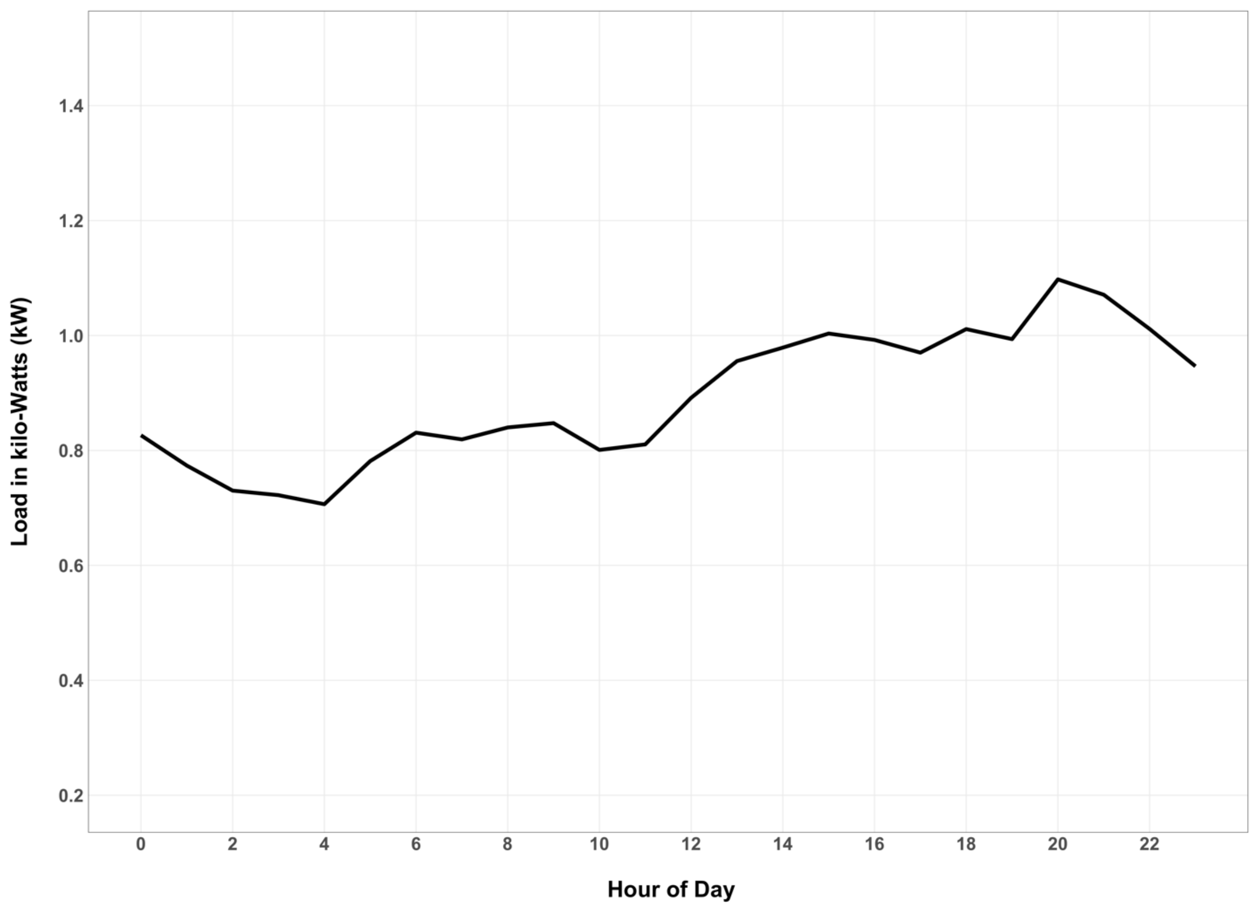

Fig. 3-4 Hourly Electric Load for Households in Lagos [46]

While all Nigerians want reliable electricity supply, economic barriers such as high fueling costs prevent most households from fully supplementing unreliable electricity grid service with backup generators. For example, surveys reported that households use their backup generators for as little as 3 – 4 hours despite receiving grid service for only 9 hours daily [13], [16]. To account for varying preferences in the number of hours per day during which households require reliable power from backup sources, I construct a set of reliability tiers. These tiers are similar to the World Bank's multi-tier framework's duration attribute for assessing electricity supply [48]. I assume that households will have a general preference to have reliable power during the evening hours after 18:00 when most members of the household are at home and awake. I also assume that households will place less value on reliability during working hours during the day when most household members are away from home. The first tier requires the availability of backup power from 18:00 to 22:00 with subsequent tiers requiring 4 more hours of backup availability than the previous tier, as described in Table 3-2. In this tier, if a grid outage occurs within these hours, the household will use their backup generators. Outside those hours, the household's load goes unmet if a grid outage occurs. In last tier, the backup generator is available at all times to meet the household load in the event of any grid outage.

Table 3-2 Tiers of Household Reliability

Reliability Tier	Hours of Backup Generator Availability per day	Hour of Day
R -4	4	18:00 – 22:00
R -8	8	18:00 – 02:00
R -12	12	18:00 – 06:00
R -16	16	18:00 – 10:00
R -20	20	18:00 – 14:00
R -24 (100%)	24	18:00 – 18:00

Table 3-3 presents the economic assumptions used in this paper for capital costs of the systems components based on quoted from local online retailers in Nigeria. I assumed a discount rate of 20% in line with the recommended value by the Nigerian regulators [49]. I also assumed an inflation rate of 10% [50]. Table B- 2 summarizes the local fuel costs in Naira/Liter, while Table B- 3 summarizes the nominal grid costs as approved by the regulators in Nigeria. Finally, for meteorological inputs I relied on hourly solar resource and ambient temperature data from HElioClim-3 v5 database [51].

Table 3-3 Economic Model Assumptions

Economic Inputs	Value
Diesel Unit cost of Operating & Maintenance, om (N/kW/h) [44]	10.5
Unit cost of Diesel Generator (N/kW) [52]	121, 000
Unit cost of Solar PV (N/kWp) [52]	318, 000
Unit cost of Battery (N/cell) [52]	86, 000
Unit cost of Inverter/Rectifier (N/kVA) [52]	45,000

Finally, I sized our residential systems using HOMER, based on the household load, different levels of backup generator availability (reliability tiers), and average durations of grid outage and grid service from [46] as summarized in Table 3-4. I assumed all technology scenarios have backup generators of size 1.5kW. Each Battery is 12V, with an amperage of 200Ah and a battery string size of 2.

Table 3-4 Summary of System Sizes for alternative technology options for Lagos household load profile

Tier	Grid + Backup Generator + Solar PV + Battery Storage (GD - BP)			
	Backup Generator Size (kW)	PV Size (kWp)	Battery Storage (#)	Inverter Size (kVA)
R -4	1.5	0.2	2	1.5
R -8		0.2	4	1.5
R -12		0.4	4	1.5
R -16		0.4	4	1.5
R -20		0.8	6	2.5
R -24		0.8	6	2.5

3.4 Results

Fig. 3-5 shows a sample day's dispatch to illustrate the effects of the backup generator availability constraint for the lowest (R-4) and highest tiers (R-24).

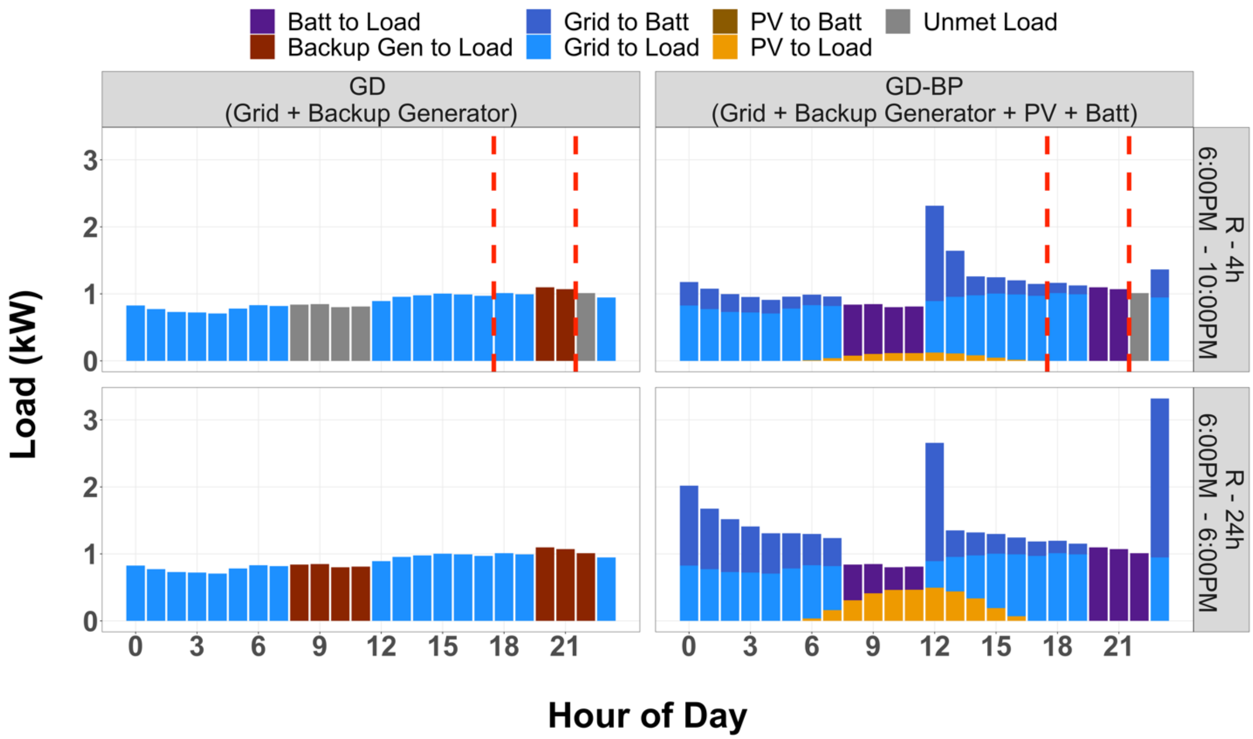

Fig. 3-5 Sample Dispatch Results. Red lines determine the range of hour of day reliability hours determined by the reliability tier.

Fig. 3-5 shows two grid outages occurred lasting for 4 hours and 3 hours respectively. The earlier outage occurs at 8AM and lasts till 12 noon (4 hours) while the second outage occurs at 8PM and lasts till 11PM (3 hours). In the R-4 backup availability scenario (upper row), in the GD configuration (top-left panel) the household's load during the first grid outage goes unmet since the time of the outage is outside the range the backup generator will be available for dispatch. The household's load in during the second grid outage is met for two hours since the outage occurs within the range the backup generator is available for dispatch. In the GD-BP configuration, the household load is only unmet at the last hour of the second outage.

In the R-24 backup availability (bottom row), all of the load during the outage hours is met by the backup generators in the GD configuration (bottom-right panel), while for the GD-BP configuration, all of the load during the outages is met with the battery storage.

Fig. 3-5 also shows the GD-BP option in both backup generator availability cases, grid consumption is greater compared to the GD as a result of grid demand used for battery charging.

Fig. 3-6 summarizes for all the technology configuration the average annual energy flows by source (grid, backup generator, battery storage or solar) and destination (to load, if positive, or to the battery storage, if negative) for the lowest and highest reliability tiers. (For full energy flows for all backup generator availability levels see Fig. B- 1in **Error! Reference source not found.**) Examining each panel in Fig. 3-6, integrating the residential will reduce both the amount of unmet household load as well as the energy flowing from the backup generator. The household reliability improves by 7 - 23% compared to the GD (See Table B- 4 in **Error! Reference source not found.**). For the highest backup generator availability (R-24), there is no unmet load since the backup generator is available at all hours to meet the load in all technology configurations.

For R-4, energy flowing from backup generators reduces by approximately 30% using the residential solar systems, while backup generator contribution to the load reduces by approximately 90.6% in the R-24 tier. The results indicate that integrating the residential electric systems could lead to significant improvements in household reliability while also reducing the household's reliance on backup generators to meet the unmet load.

Fig. 3-6 also shows that the presence of battery storage increases grid consumption since the dispatch model allows for grid charging battery charging when the grid is available. In the R-4 tier, grid consumption also increases by approximately 28.5% in the GD-BP.

Integrating these systems also increases the maximum hourly peak demand as shown in Fig. 3-5. The peak hourly grid demand rises by 2.5 - 3.5 in the GD-BP technology scenario compared to the peak hourly grid demand in the GD. The magnitude of the peak demand depends on the size of battery storage used (See Table B- 4 in **Error! Reference source not found.**). The results suggest that the presence of grid storage could potentially add pressure to an already constrained grid and could potentially increase the frequency of outages if these systems are widely adopted[53], [54].

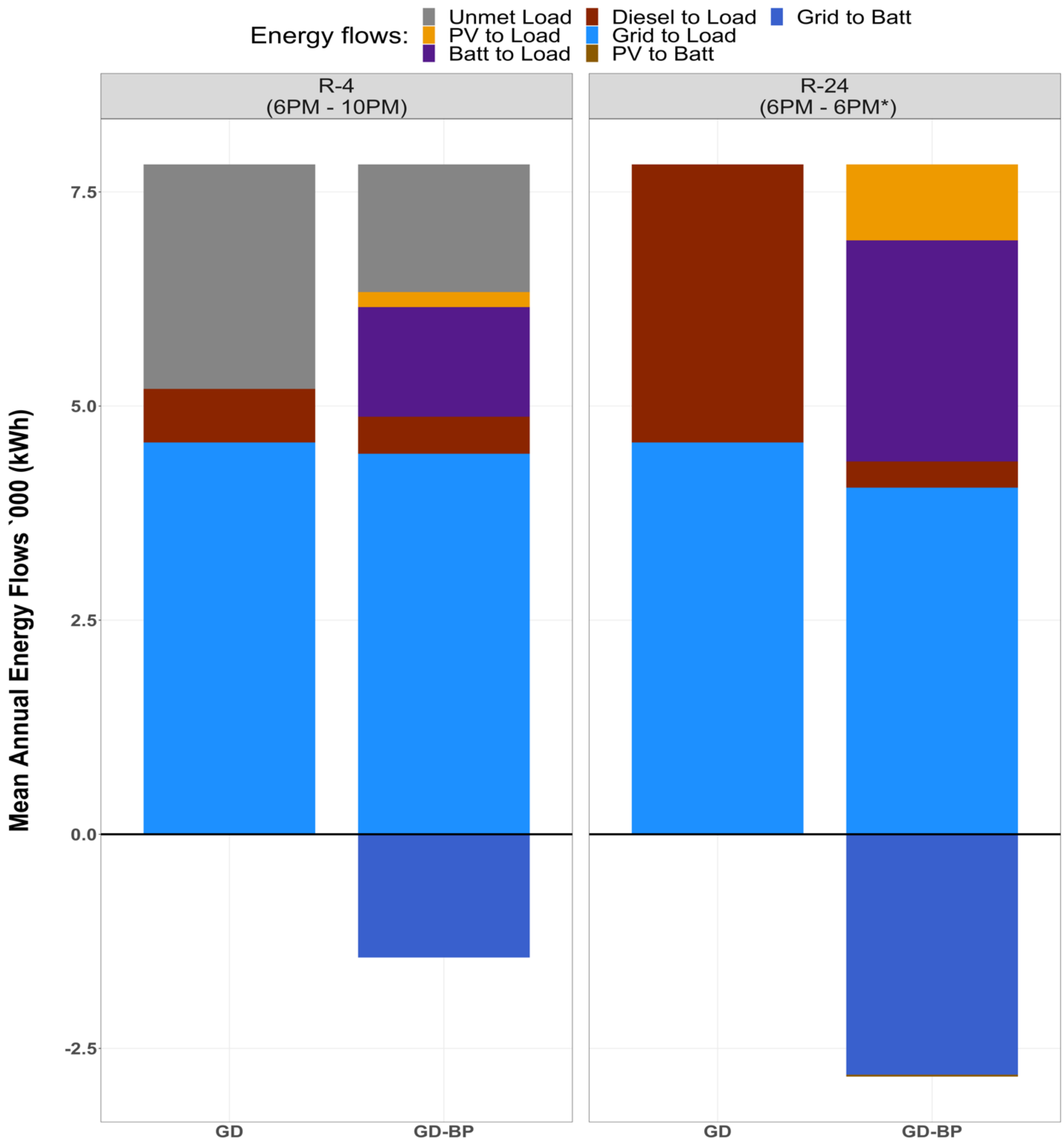

Fig. 3-6 Average Annual Energy Flows for backup generator availability levels considered for Lagos Load profile.

Fig. 3-7 shows the economic implications of integrating the residential electric systems for the Lagos household profile in terms of Net Present Costs (NPC) for all technology configurations considered. The results show using the base the base technology (GD), the net present costs rise from 1.2 million naira (R-4) to 3.1 million Naira (R-24). For the same grid availability, the household must spend 2.5 times to the amount to provide at least 4 hours of electricity daily in order to guarantee full reliability. With the residential solar electric systems, the net present costs rise from 1.5 million naira to 2.2 million naira. Compared to the GD technology, the improved reliability need is not driven significantly by increased backup generator use but by the battery storage. The results also show that investing in the residential systems is not universally economical, as the net present costs using these systems only becomes lower than the base technology when the household has the backup generator availability for greater than 12 hours daily.

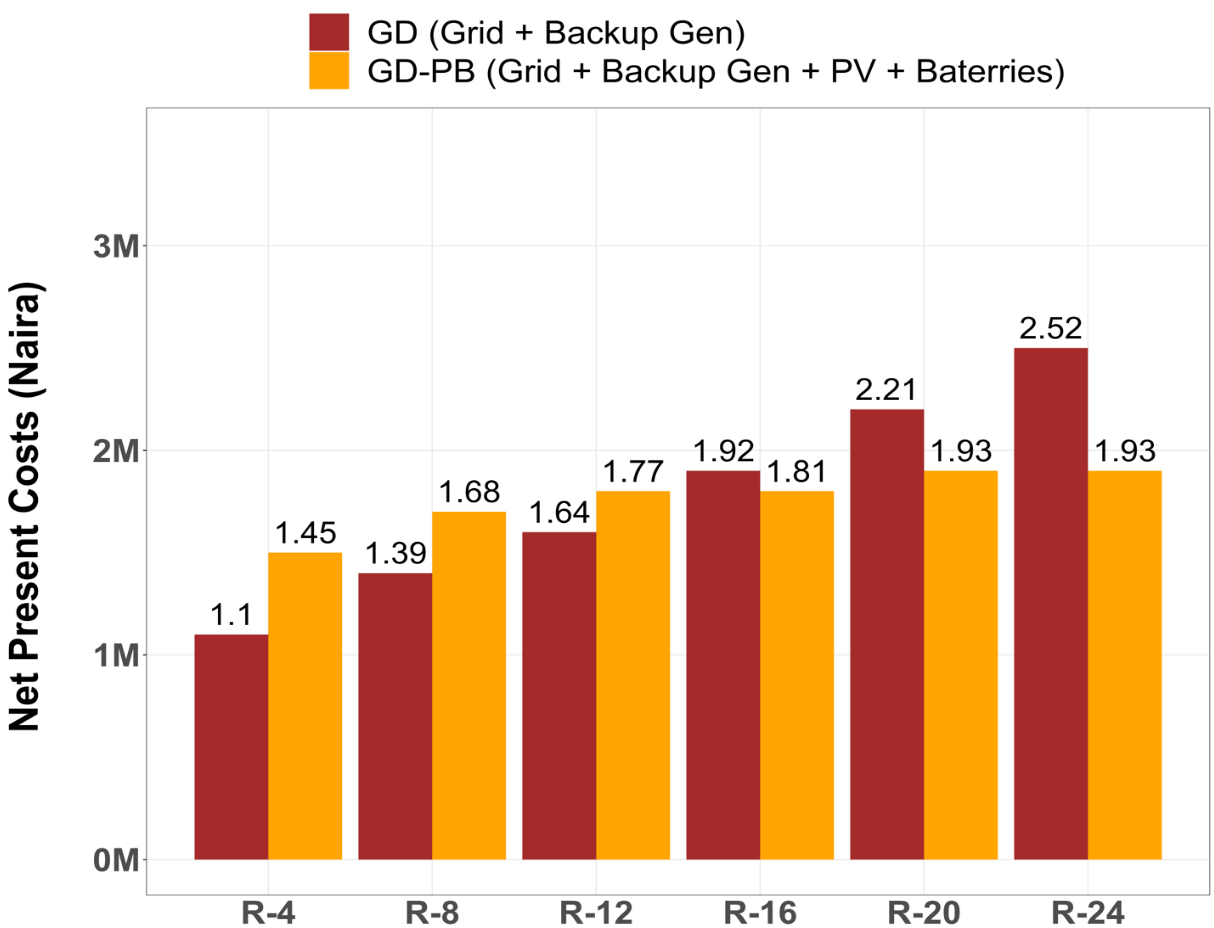

Fig. 3-7 Net Present Costs for Lagos load profile across all backup generator availability levels

3.4.1 Sensitivity Analysis

I identified in the previous section that level of backup generator related expenditure particularly fueling costs affect the economic attractiveness of the alternative systems (See Fig. B- 2 in **Error! Reference source not found.**). The factors that affect backup generator related expenditure include grid availability, and generator type and fuel. Also, I investigate the effects of economic parameters like discount rate, since the alternative electric systems require high upfront costs and lower operating costs compared to backup generators with lower up-front costs but higher operating costs.

Effects of Grid Reliability

Dispatching backup generator to meet the household's load is primarily determined by the level of grid service, so changes in the level of grid availability will impact the economic attractiveness of the systems. Hence, I tested the effects different grid availability levels using the parameters provided from the End-use Metering Campaign for Residential Houses [46].
For each grid availability level, I resized our systems in HOMER (See Table B- 5 for all sizes in **Error! Reference source not found.**). Fig. 3-8 illustrates the effects of grid availability on the economic attractiveness of the residential solar electric systems. As grid availability improves, the net present costs reduce since the household receives more electricity from the grid which is a cheaper source that the backup generator. This is illustrated with the downward slope as the grid availability increases.
At very high levels of grid availability (greater than our base 60%), using the residential solar electric systems is not economically attractive which is unsurprising since the value of these systems is in reducing backup generator use, which will already be reduced by improved grid reliability.

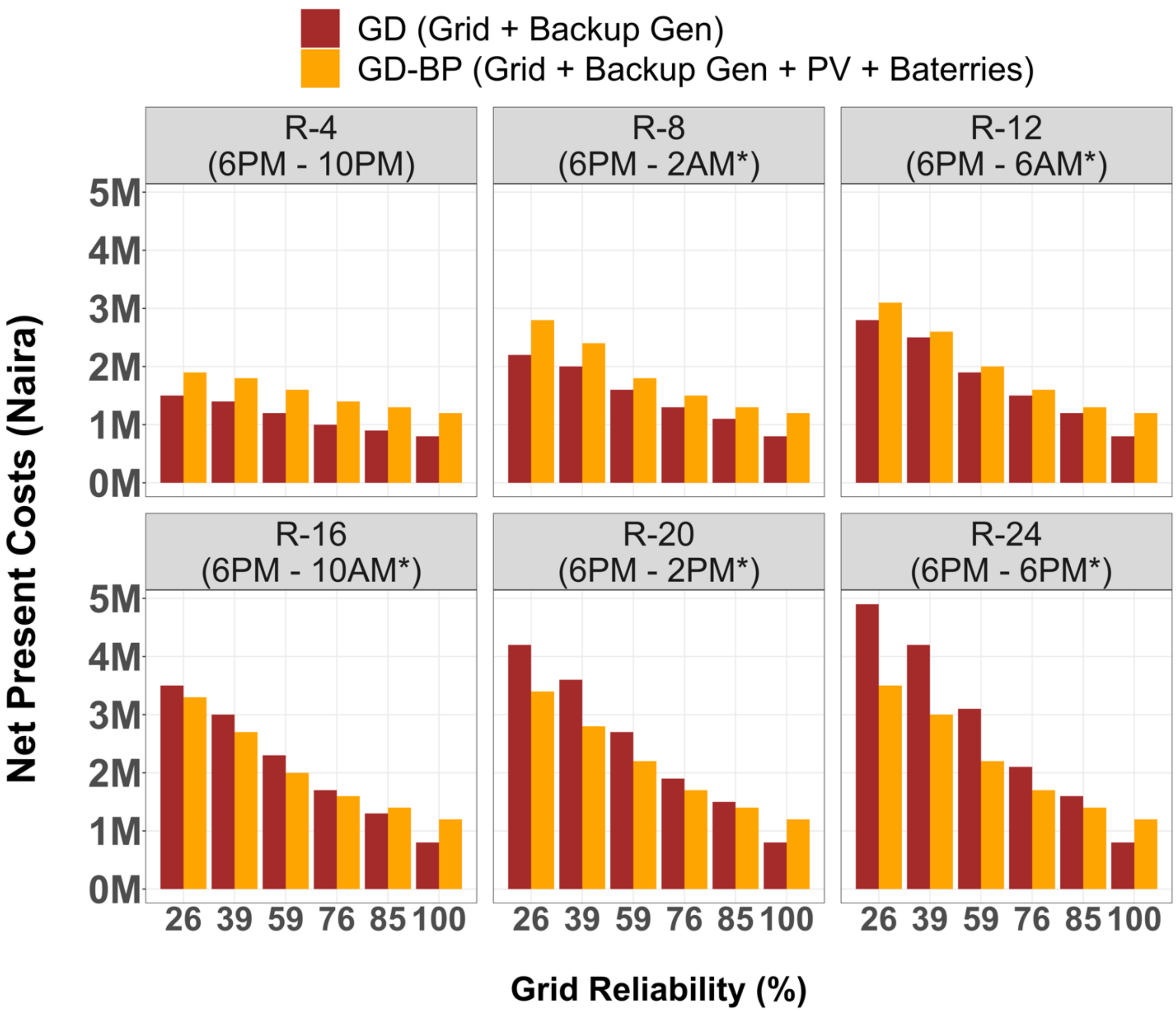

Fig. 3-8 Effects on grid availability on economic attractiveness of alternative electric systems

Effects of Discount Rates

Developing countries like Nigeria are typically characterized by high interest rates. Commercial interest rates to households are range between 20% - 25% (NERC, 2017). These high interest rates will therefore be less favorable to the residential electric systems since the require larger up-front costs compared to backup generators with lower up-front costs but higher operating costs. I conducted a sensitivity analysis to determine the effects in terms of economic attractiveness as shown in Fig. 3-9. With lower discount rates, the economic attractiveness of the residential solar electric systems improves even at lower backup generator availability levels (but not for R-4). This suggests that access to cheaper capital costs could significantly improve uptake of these residential systems.

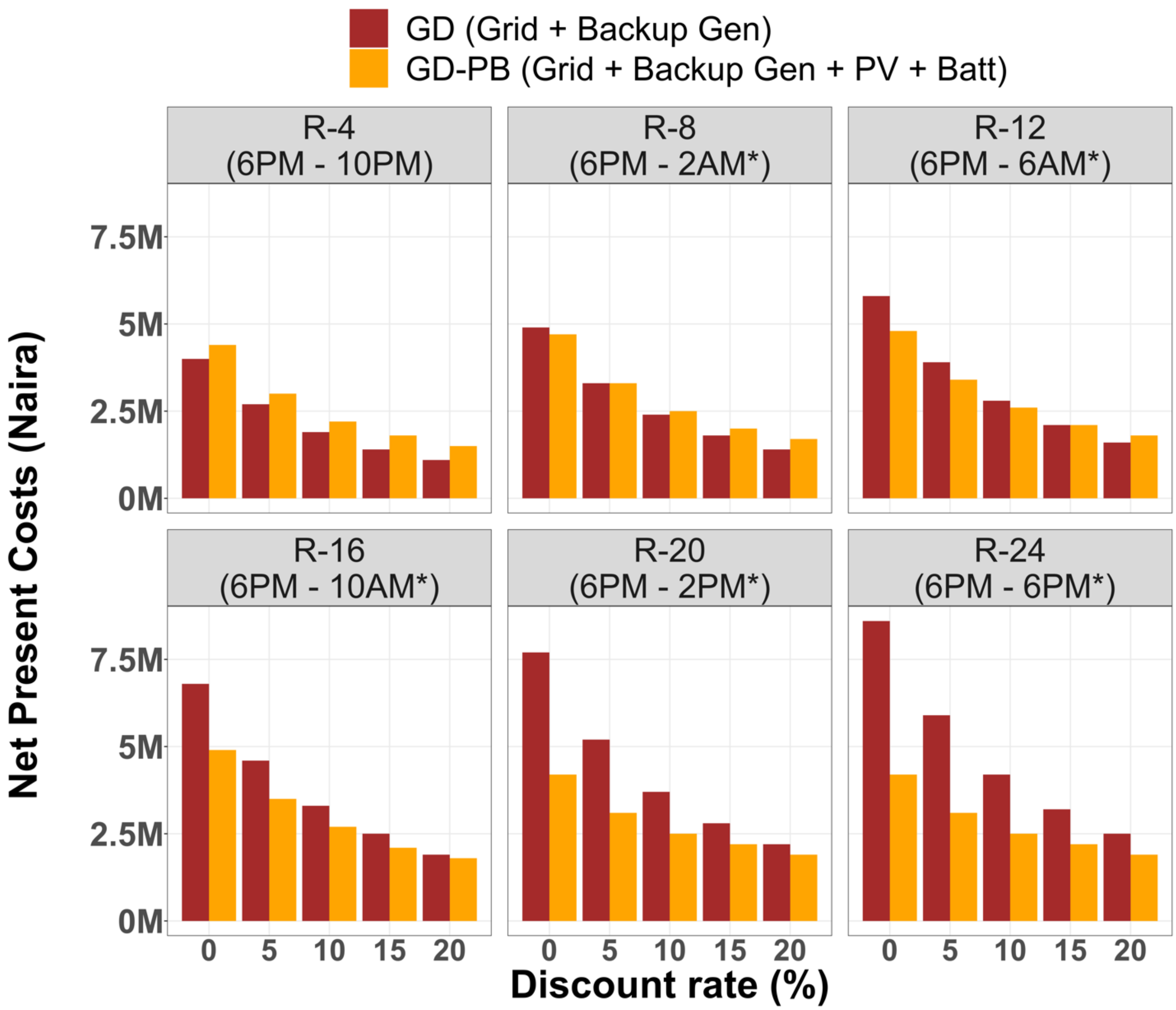

Fig. 3-9 Effects of discount rate on economic attractiveness of alternative electric systems

Backup Generator Type and Fuel Price

Households in Nigeria could also use petrol generators to meet their electricity needs. The capital cost of the generator is lower compared to the diesel generator, and the cost of fueling is also lower as a result of the subsidization policy in Nigeria. In 2018, the pump price of diesel in Lagos was N217 while the pump price for petrol was N145. However, petrol generators are less efficient that diesel generators. Fig. 3-10 shows similar results to our base results. Even when using the petrol generators, households in Lagos who have their backup generators for at least 12 hours daily will find these systems economically attractive.

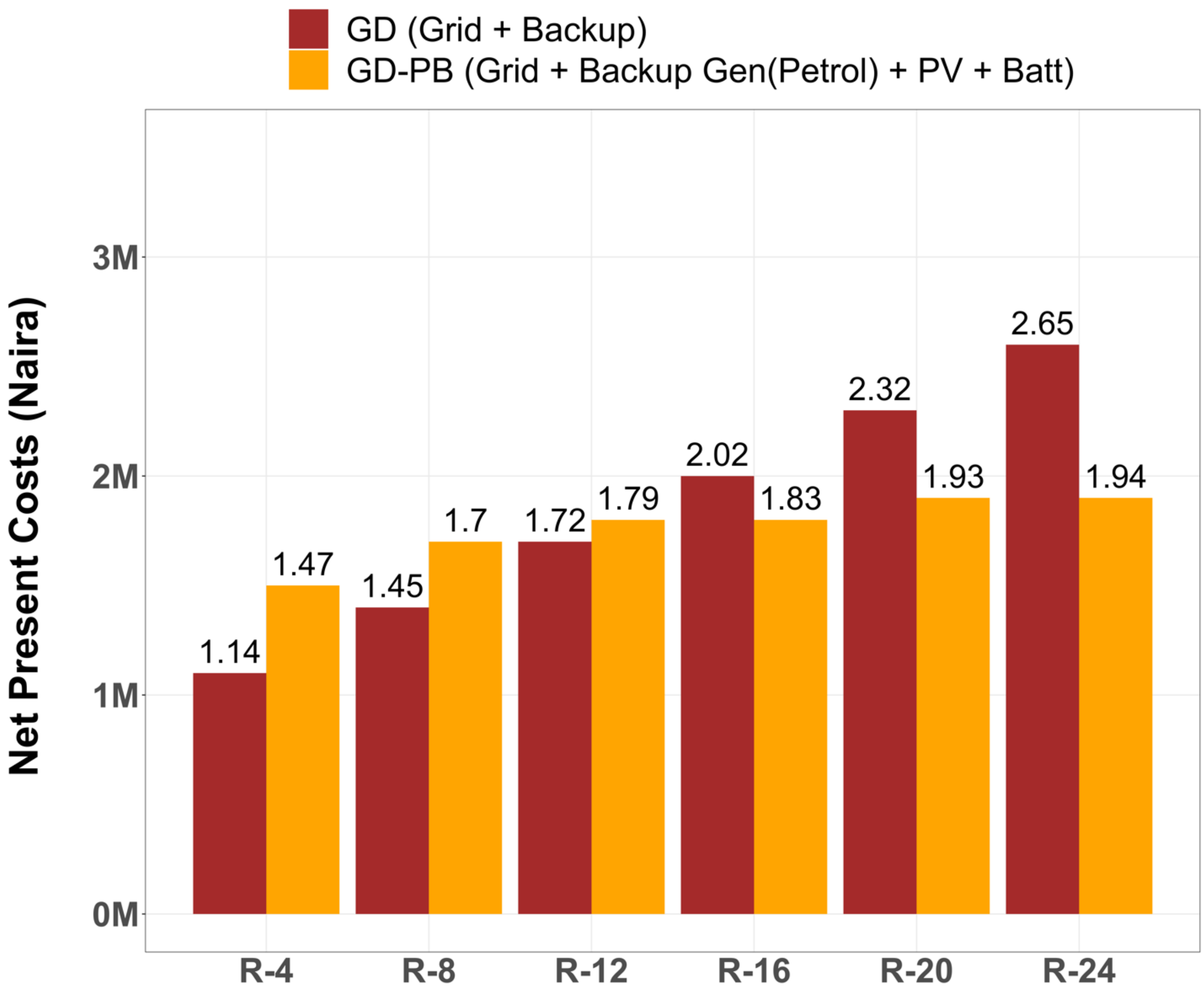

Fig. 3-10 Effects of Backup Generator Availability on Economic Attractiveness using Petrol Generators

Other Residential Systems: Battery Only Systems

Finally, I performed the economic analysis using only the battery storage. Similarly, I sized the systems using HOMER as shown in Table B- 6 **Error! Reference source not found.**). Similarly, Fig. 3-11 shows the battery storage only systems achieves lower net present costs when the Lagos household has their backup generators available for at least 16 hours daily to provide for the electricity needs not provided by the grid.

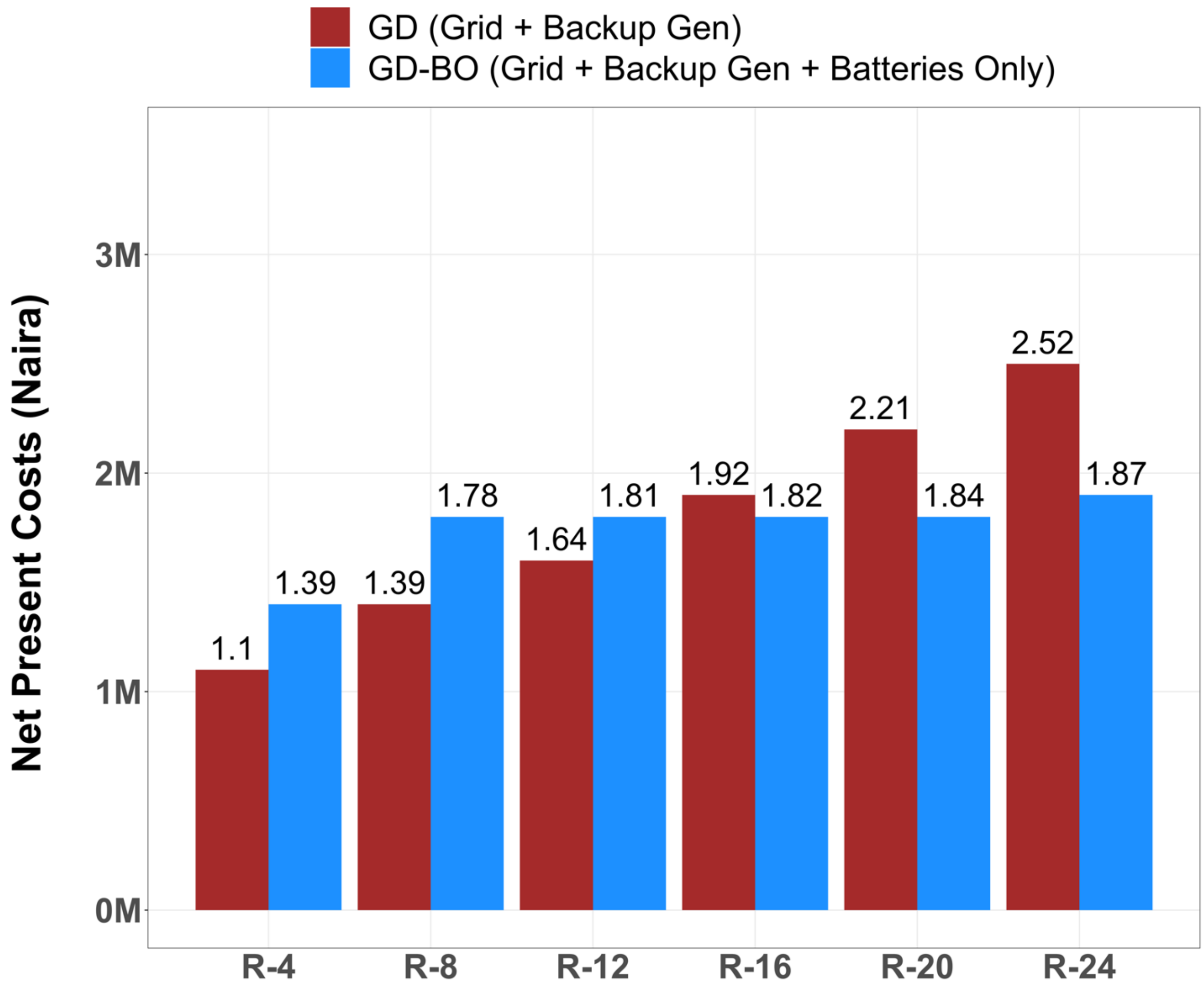

Fig. 3-11 Economic comparison using Batteries Only

3.5 Discussions

This chapter examined the economic attractiveness of residential solar systems with battery storage in a Lagos household experiencing unreliable grid service. I modelled the operation of these systems as they would be typically deployed operating with the existing electricity generating options (grid and backup generators), while explicitly considering grid unreliability and varying levels of backup generators availability based on household daily reliability needs. Using the base grid reliability for Lagos provided (approx. 59%), households can improve their electricity reliability (i.e. percentage of times the household's load is met) using their backup generators, or residential solar systems. Using their backup generators alone, households can improve their reliability by 10 -70% depending on the level of the backup generator availability level. Using the residential solar with their backup generators (GD-PB), the households can improve their reliability 35 to 70%. Therefore, a household with the residential systems meets more of its electricity needs compared to a household without the system and has to rely on backup generators alone.

Economically, the results show that using residential solar systems reduce reliance on backup generators, and all the associated backup generator expenditure (fuel, operating and maintenance, replacement) by 32% to 90%. Our results also show that grid expenditures increase as a result of greater grid demand to charge the batteries. The grid expenditure in the base case (GD), was approximately N0.47 million naira, and using the residential solar systems increase grid expenditure by 29%- 49%. This finding could concern system operators, as the increase in grid demand could increase pressure on their already constrained networks and could lead to further blackouts and brownouts if penetration of battery storage systems rises. The network stability impacts of increased battery storage penetration is poorly understood, therefore further research should focus on examining the potential the impacts of large penetrations of battery storage systems on grid network stability.

Despite reductions in household reliance on backup generators and improvements in household reliability, the results show that integrating the residential solar systems is economically attractive to households who want higher levels of electricity service and can afford to have their backup generators available to meet their load during outages for greater than 12 hours. Below this level of backup generator availability, the savings from the diesel expenditures do not justify the investments in these systems.

The sensitivity results show that the grid availability affects the economic attractiveness of the residential solar systems since it determines how households use their backup generators. Expectedly, better grid reliability thus replaces a greater share of electricity generated by backup generators, and thus limits the potential savings that these residential solar systems requires to be economically attractive to households. Also, lower discount rate improves the economic attractiveness of these systems. The minimum reliability demands did not change when I considered only battery storage only systems or households using petrol generators.

I note some caveats about these detailed results. First, data quality on grid service in Nigeria is challenge for analysis of this nature. The true distribution of outages in Nigeria is uncertain, and this analysis makes assumes a stochastic nature of distribution of the duration of grid service and grid outages. Given this stochastic assumption, I reported only a single run of the grid schedule due to the computational demand necessarily to perform a full Monte- Carlo analysis. However, given hourly resolution of our analysis and the model horizon of 15 years, I expect the variations to level out and thus not significantly impact the results, particularly qualitatively.

4 An Assessment of the Emissions Savings potential of Residential Solar Systems with Battery Storage in Lagos Households Experiencing Unreliable Grid Service

4.1 Introduction

The finds from Chapter 3 shows that residential solar electric systems reduce reliance on backup generators. Beyond the economic implications of this conclusions, reducing reliance on backup generators could also have implications on emissions. Studies have found that backup generation leads to increased emissions in Nigeria, but direct emissions from household backup generators has not received enough investigation, even though majority of the end users of electricity is in the residential sector[14].

In this chapter, I attempt to estimate the emissions implications from household's use of backup generators in response to unreliable grid service, as well as the potential for the residential solar electric systems explored in the previous chapter to lower air emissions as a result of reduced reliance on backup generators. This builds from the results of the previous chapter by investigating the broader implications on household's reliance on backup generators in terms of the magnitude of air pollutants emitted as a result of the household's response to unreliable grid service.

4.2 Data Sources and Methods

The two sources of emissions analyzed are from the grid, and from backup generators. I have assumed the household uses diesel-based backup generators to meet load when the grid is unavailable. I quantify the following air emissions following carbon dioxide (CO2), fine particulate matter, ($PM_{2.5}$), carbon monoxide (CO); Sulphur oxides (SOx); and Nitrogen oxides (NOx) for Lagos since it has the greatest number of electrified households in Nigeria with an electrification rate of 99% (See Appendix C Demographic Data for Lagos Households Table C- 1). To quantify the emissions from the household and grid, I utilized two outputs from the dispatch model in the previous chapter, namely fuel consumption and grid consumption.

4.2.1 Environmental Model

For each backup generator availability level, grid schedule, and technology configuration the total pollutants emitted from the backup generator is given by Eq.(4-1)

$$Pol_P = \zeta_{PD} \cdot \sum_{y=1}^{15} \sum_{h=1}^{8760} \mathrm{F}_{\mathrm{D-L}}[\mathrm{h,y}] \qquad (4\text{-}1)$$

Where Pol_P is the lifetime emissions of pollutant, P; ζ_{PD} is the emissions factor for P from the backup generators, $F_{D\text{-}L}[h,y]$ is the fuel consumption in hour (h) during year(y) from running backup generators. I obtained emissions factors from previous studies[12], the World Bank report on diesel emissions in Nigeria[55], and the International Energy Agency[34], [56].

Similarly, the total emissions of pollutant, P, from the grid is given by E.(4-2)

$$Pol_P = \zeta_{PG} \cdot \sum_{y=1}^{15} \sum_{h=1}^{8760} \mathrm{F}_{\mathrm{G-T}}[\mathrm{h,y}] \qquad (4\text{-}2)$$

Where Pol_T is the lifetime emissions based on technology scenario, T; ζ_{PG} is the emissions factor for P emitter by the grid, $F_{G\text{-}T}[h,y]$ is the grid consumption in kilo-Watts in hour (h) during year(y). For the grid emissions, I relied on data reporting Nigeria's on-grid electricity generation mix which is dominated by natural gas (75%) and hydro(25%)[57]–[59]. I obtained the grid emissions factors in a literature review of grid level emissions factors [60], [61]. The emissions factors for grid and backup diesel generated pollutants are reported in Table 4-1

Table 4-1 Emissions factors used in the analysis from diesel backup generators and the grid

Pollutant	Emissions factor of Diesel ζ_D (kg-Pol/liter)	Emissions factor of the Grid ζ_G (kg-Pol/kWh)
Carbon Dioxide (CO_2)	2.62 [12]	416 x 10^{-3}
Carbon Monoxide (CO)	1.5 x10^{-2}	0.328 x 10^{-3}
Particulate Matter ($PM_{2.5}$)	5.02 x10^{-3}	0.007 x 10^{-3}
Nitrogen Oxide (NO_X)	6.99 x10^{-2}	0.802 x 10^{-3}
Sulphur Oxide (SO_X)	3.17 x10^{-3}	0.02 10^{-3}

4.3 Results

Fig. 4-1 shows that across all backup generator availability levels, using the residential electric systems reduces of annual fuel consumption for households in Lagos based on the results in Chapter 3. Without the residential solar systems, a household using backup generator to provide at least 4 hours of electricity daily consumes 250 liters annually. This value rises to 1350 liters annually to provide 100% reliability (R-24) daily. With the residential solar systems, our results show the household in Lagos will reduce consumption to 170 liters annually guarantee at least 4 hours of electricity daily. Our results show that diesel consumption reduces in this technology to 130 liters annually to provide 100% reliability (R-24) daily. This is because comparatively, the number of batteries used in this R-24 tier is greater (6 batteries (R-24) compared to 2 (R-4)).

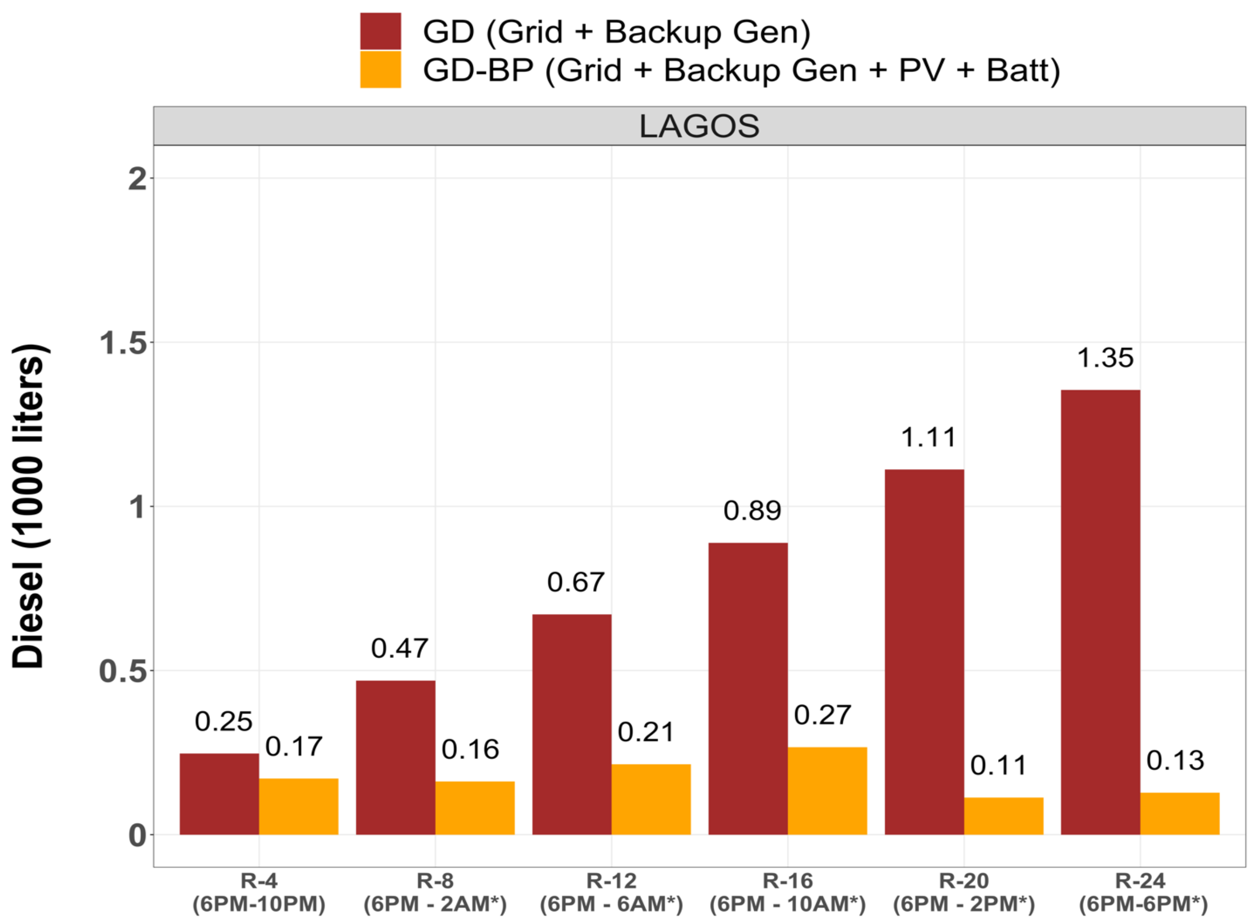

Fig. 4-1 Annual Average Household Diesel Fuel Consumption by backup generator availability level

Fig. 4-2 shows that integrating these systems increases grid consumption (when the grid it is available), as a result of using grid supplied electricity to charge batteries. Without the residential systems, the household consumes the same level of grid electricity at 4,600 kilowatt-hours (kWh) for both backup generator reliability levels. This is because grid supply is independent of household reliability needs and wouldn't change even if the household demands more electricity. Using the residential solar (GD-BP), grid consumption rises by 1300- 2300 kWh annually depending on the size of the battery storage in the backup generator availability level (See Table 3-4).

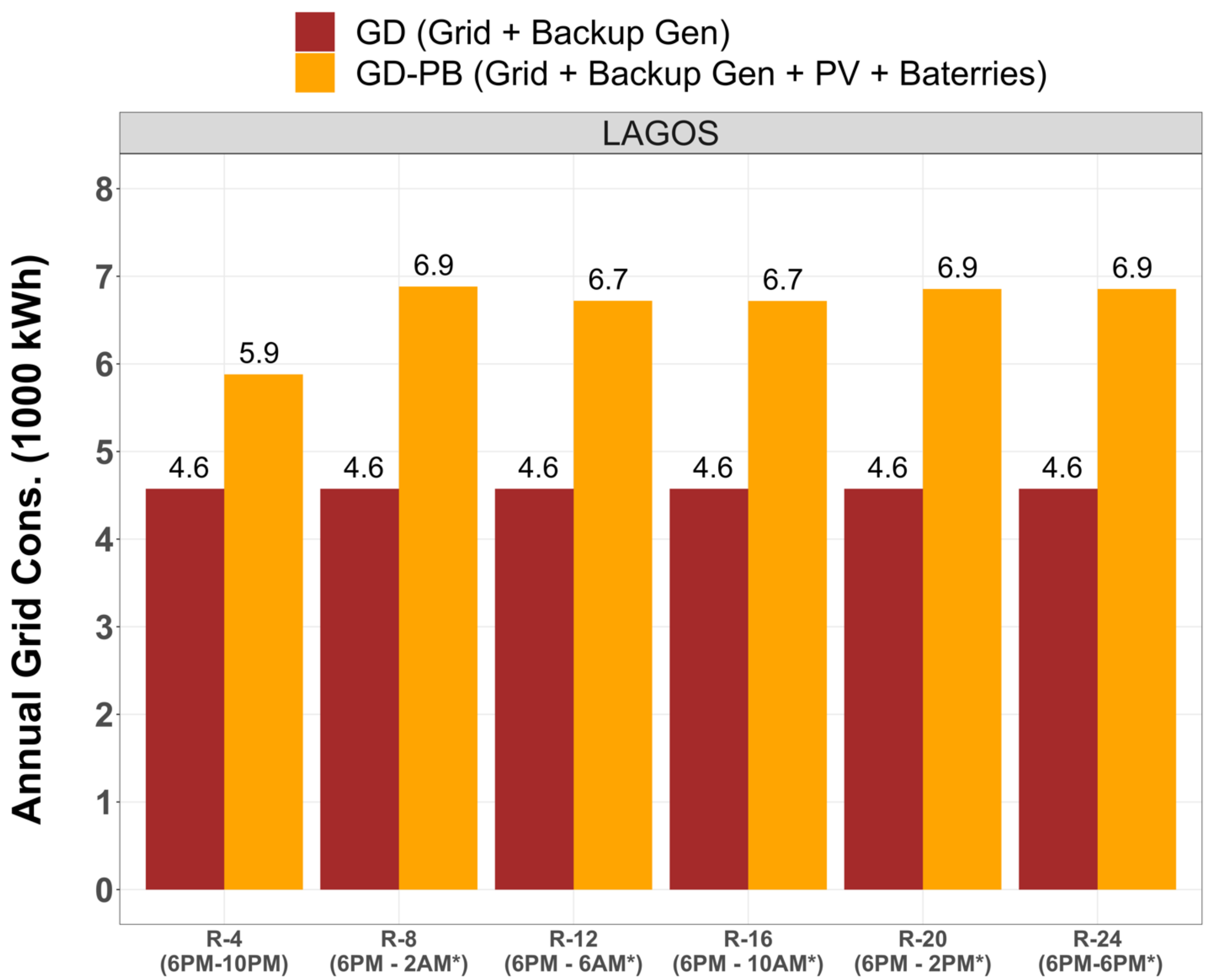

Fig. 4-2 Annual Average Household Grid Consumption by State

Fig. 4-3 illustrates the annual emissions amounts in kilograms for Lagos households using the fuel and grid consumption inputs and emissions factors considering all the backup generator availability levels. Each row represents the pollutants considered: CO2, PM2.5, NOx and SOx emissions. For all pollutants except carbon dioxide, using the residential solar systems reduces the amount of emissions. For the R-4 and R-8 level, our results show that overall household emissions for CO2 increases with the residential solar electric systems. This was primarily driven by the emissions from the grid even though emissions from the backup generators reduced. Annual CO_2 emissions from the backup generators reduced from 647kg (GD) and 448kg (GD-BP). Annual CO_2 emissions from the grid increases by 1903kg (GD) to 2440 kg (GD-BP). At higher backup generator availability levels, the emissions saved from reduced backup generator use outweighs the additional emissions from increased grid demand.

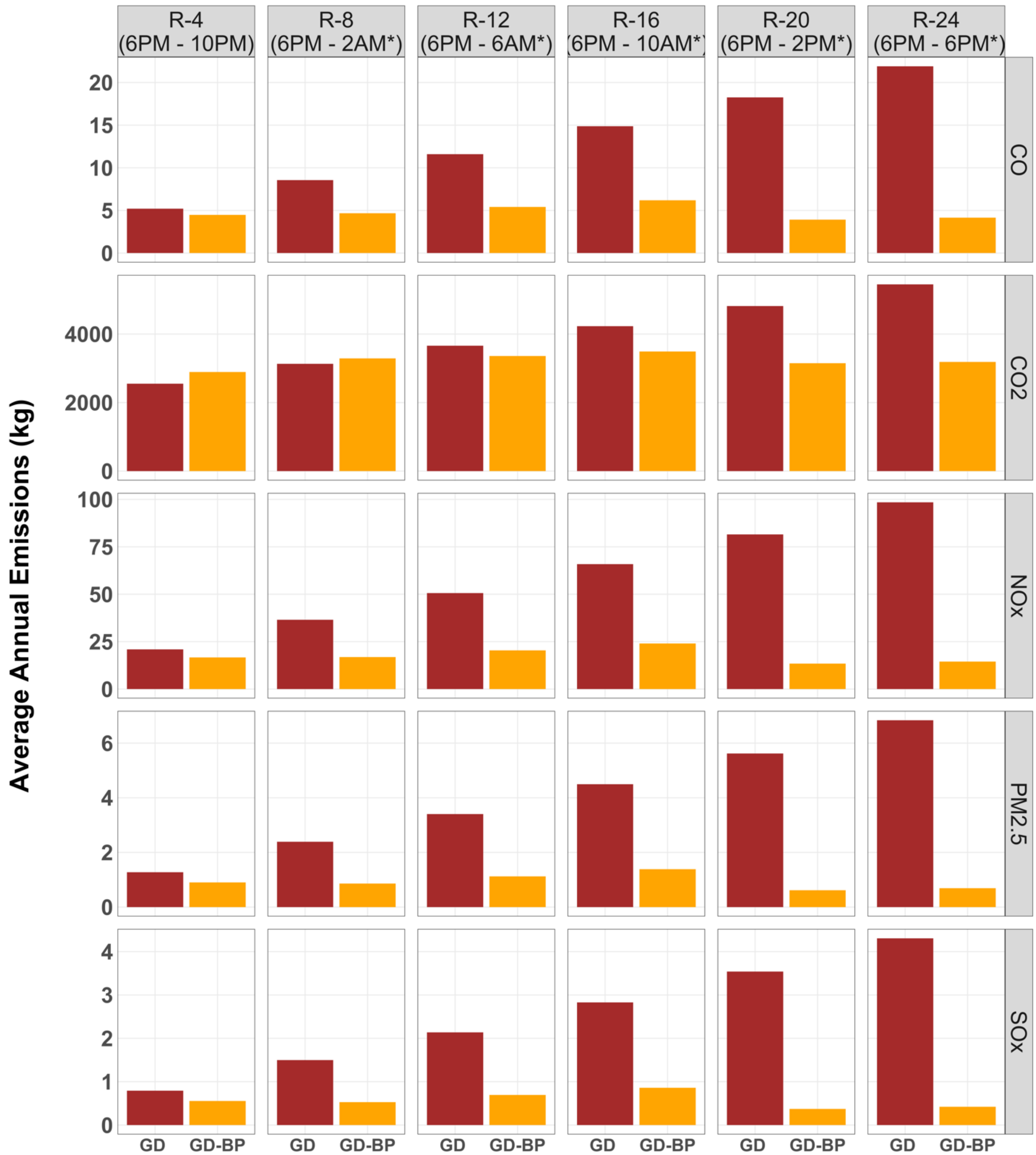

Fig. 4-3 Annual Household Emissions from Grid and Backup Generators for Lagos Household

Based on the insights from Chapter 3, I tested the effects of grid reliability on the overall household emissions for all the emissions considered. Fig. 4-4 illustrates the effects on grid availability on overall household CO_2 emissions. Each panel shows the annual emissions for a given level of backup generator availability. At the lowest level of backup generator availability, the results show an increase in emissions with increasing grid reliability. This is because portions of the household electricity load go unmet, and this unmet load does not produce any emissions. With increasing grid availability, the household's unmet load is increasingly replaced by the grid hence resulting in increased CO2 emissions. With the residential solar systems, the greater demand from the grid to charge the batteries when the grid is available increases the resulting emissions. With higher backup generator availability levels, more portions of the household's load not provided by the grid is met with greater dispatch from the backup generators, which is a higher polluting source. So, at lower levels of grid reliability and higher backup generator availability, the household's CO2 emissions is much larger in the GD compared to GD-BP.

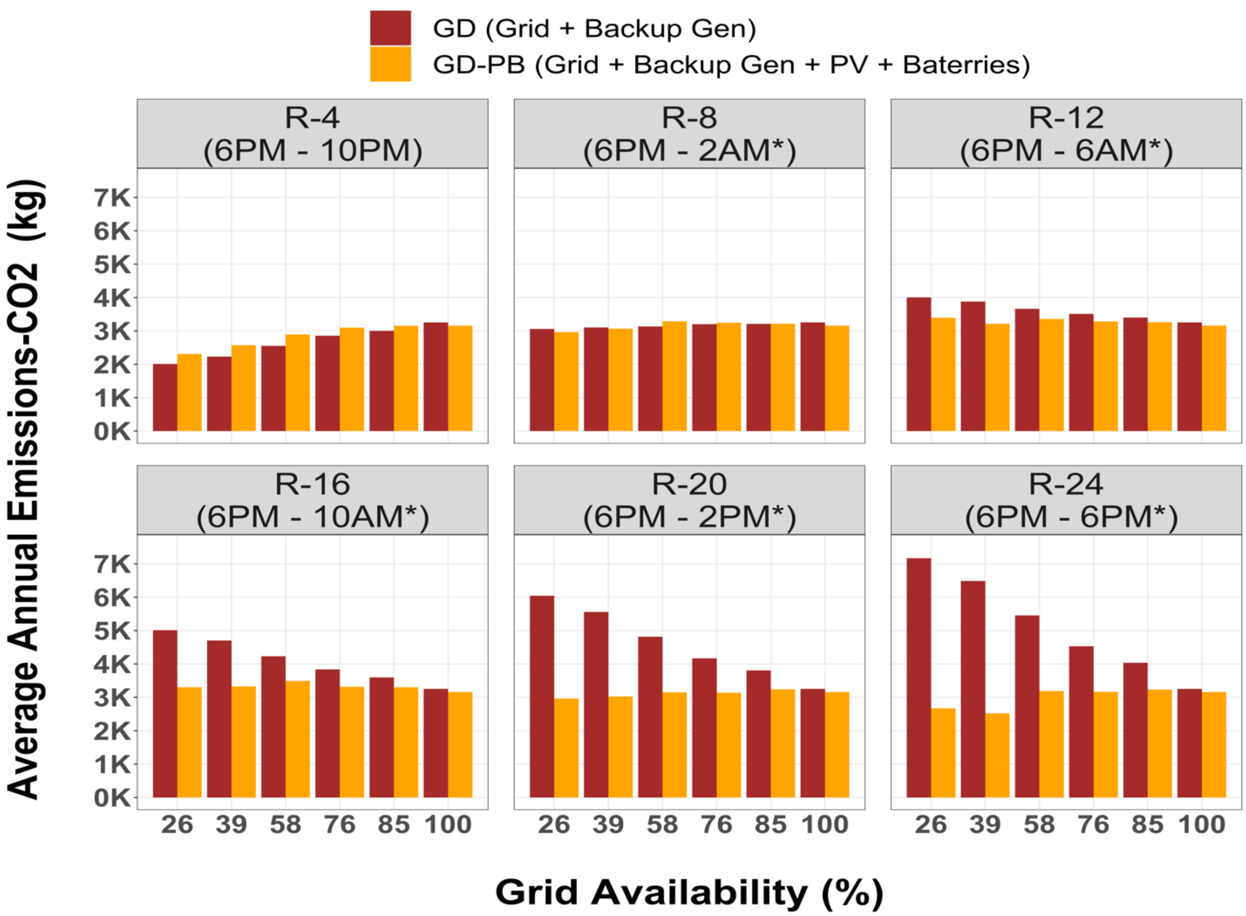

Fig. 4-4 Effects of Grid Availability on overall annual emissions

I extrapolated the results in Fig. 4-3 to estimate the potential magnitude of emissions for grid connected households in Lagos as a result of the households use of backup generators in response to unreliable grid service, and the potential savings if all households used either of the alternative residential electric systems. I obtained demographic data on population, household size, and the National Bureau of Statistics [62], and electrification rates from the World Bank on electrification in Nigeria [47]. Table 4-2 shows the estimates of the range of total annual emissions produced by grid connected households in Lagos assuming the lowest (R-4) and highest (R-24) backup generator availability.

Table 4-2 Estimates of total Household Emissions from Backup Generators for all households in Lagos in million Tons-

	Grid + Diesel GD-BP	Grid + Diesel + PV+ Battery Storage (GD-BP)
Carbon Dioxide CO_2	8.4 – 18	9.5 – 10.5
Particulate Matter PM2.5	1.27 – 6.8	0.89 – 0.691
Nitrous Oxide - NOx	20.9 – 98.4	16.7 – 14.5
Sulphur Oxide-SOx	0.79 – 4.31	0.552 – .420
Carbon Monoxide -CO	5.2 – 21.9	4.48 – 4.15

The extrapolations show that the use of backup generators in response to unreliable grid service results in households emitting significant amounts of the five pollutants examined. For example, CO_2 emissions in households without the residential solar systems range from 8.4 million metric tonnes to 18 million metric tonnes. If all households use the residential systems CO_2 could potentially range from 9.5 million metric tonnes to 10.5 million metric tonnes. To put in context, Nigeria aims to reduce greenhouse gas emissions by 478 million metric tonnes annually. Households in Lagos alone could potentially contribute up to 0.25% - 1.6% towards the target reduction.

4.4 Discussion

In this chapter, I analyze the household emissions implications of unreliable grid service for in Lagos, as well as the emissions reducing potential of alternative electric systems like battery storage systems, and solar panels with battery storage. The results suggest that residential solar systems with battery storage systems can reduce significant amounts of air pollutants which have significant impacts on health and the climate. Similar to the insights of Chapter 3, the results show that that the level of emissions, and the potential savings, is primarily driven by the level of reliability needed by the households. This is because it governs how much the household's backup generators will be available for dispatch. Households that obtain full reliability with backup generators consume up to five times the level of fuel consumption, and thus six times the pollution compared to households with the lowest reliability needs we considered.

This finding is particularly interesting to policymakers as reduction in backup generator use, also results in reductions in emissions of which the quantification of the benefits in terms of economic damages was beyond the scope of this chapter. Given the strong attention paid to greenhouse gas emissions reductions by the Nigerian government, outlined in the Nigerian Nationally Determination of Contribution[63], I can conclude that our results suggesting the avoided emissions because of these alternative electric systems should attract the attention of policymakers.

Also, the residential solar electric systems show its potential in improving air quality in Lagos by reducing air pollutants such as $PM_{2.5}$. Although, our work does not quantify the health damages associated with emissions from backup generators because analyses of this type would require a full inventory of all the emissions sources linked to chemical transport models as well as dose-response models for households in Lagos Nigeria. The results from this chapter serves as the first step in quantify the magnitude of emissions arising from heavy reliance of backup generators as a result of unreliable grid service. With better data, the results of this paper could be used in quantify the potential benefits of the residential solar systems in reducing mortality and morbidity risk. This would further underscore the potential of these systems in address the multi-dimensional challenges of providing reliable electricity service in Nigeria.

5 Conclusions

While the grid slowly grows to provide better access and reliability, households have to take matters into their own hands to provide the energy needed to meet their needs. It is during the slow transitional phase of grid extension and improvements that intermediate technological interventions such as minigrid and solar home systems could intervene to provide cleaner and potentially cost-effective alternatives. First to provide the reliable service while also reducing and potentially eliminating reliance on fossil-based solutions and all its negative externalities which have short- and long-term consequences. This thesis through a quantitative investigation of residential solar systems to analyzed technical, economic, and environmental merits of residential solar systems potential to address key electricity challenges facing sub-Saharan households.

For households in rural areas without access in Kenya, solar home systems provide a cost-effective alternative to kerosene lamps as a better lighting alternative, and even better for household economics when the additional services are considered like phone charging. Our results show that the benefits of replacing kerosene transcend households to society as a result of reduced greenhouse emissions from burning kerosene. The key determinant of economic attractiveness, I found was price elasticity of demand for lighting services, which attempts to quantify the value households place on improved lighting service. However, it is unclear whether households value lighting in this way, and thus is the subject of future work.

In this thesis, I also found that residential systems could create economic value to households in grid connected household with unreliable grid service, an application for these systems that has not been properly investigated. I found that residential solar with battery storage can provide improved household electricity reliability while reducing reliance on backup generators. Achieving these benefits comes at the cost, as the residential solar systems increases grid demand and expenditure. This could negatively impact grid stability if deployment of these systems continues to grow, and further worsen an already constrained network. I identified that the main driver of the economic attractiveness of these systems are the household's reliability needs which is reflected in how many hours the household's backup generators is available for dispatch in the event of a grid outage. Household must have their backup generators available for greater than 12 hours daily to find these systems economical. I also found that grid availability is also a key determinant of the economic attractiveness of the residential systems, because the improved grid availability replaces backup generator electricity and thus potential savings opportunities for the residential systems required to be economically attractive. From an emissions standpoint, I found that the residential systems could reduce emissions for air pollutants and greenhouse gases. Households requiring and high reliability needs and meeting these needs with their backup generators being the best prospects for economic savings, and emissions reductions

The results of the thesis could be helpful in informing policymakers interested in options for reducing negative externalities of household reliance on fossil fuel backup generators. The results show that these systems can reduce reliance on backup generators and thus fueling demand for backup generation. This suggests that the Nigerian government could save on imported and subsidized petroleum products. Also, the reduction in greenhouse emissions by using these residential systems could aid the Nigerian government's efforts to reducing greenhouse emissions by 2030.

This thesis is a step in understanding the applicability and broader technical implications of residential solar systems in addressing the energy challenges in developing countries particularly for grid connected households, but much more work needs to be done. The current modelling technique for unreliable grid service assumes a stochastic distribution of grid service and grid outages, which ignores possible temporal and systemic correlations. The goal of future research will be to obtain better quality time series data over a long period of time to capture seasonal effects of grid performance. While the thesis provides an insight to the emissions reducing potential of these household level systems, I have investigated and compared no other option policymakers have available to reduce greenhouse gas emissions to explore the cost effectiveness. Future work will comparatively analyze of the economic and environmental implications of all the strategic policies outlined in Nigeria's INDC.

6 Appendix A BBOXX Supplemental Information

The SHS provider followed a specific data logging sequence to conserve bandwidth when receiving data from their remote systems. The process are described in the flow charts in Fig. A- 1and Fig. A- 2

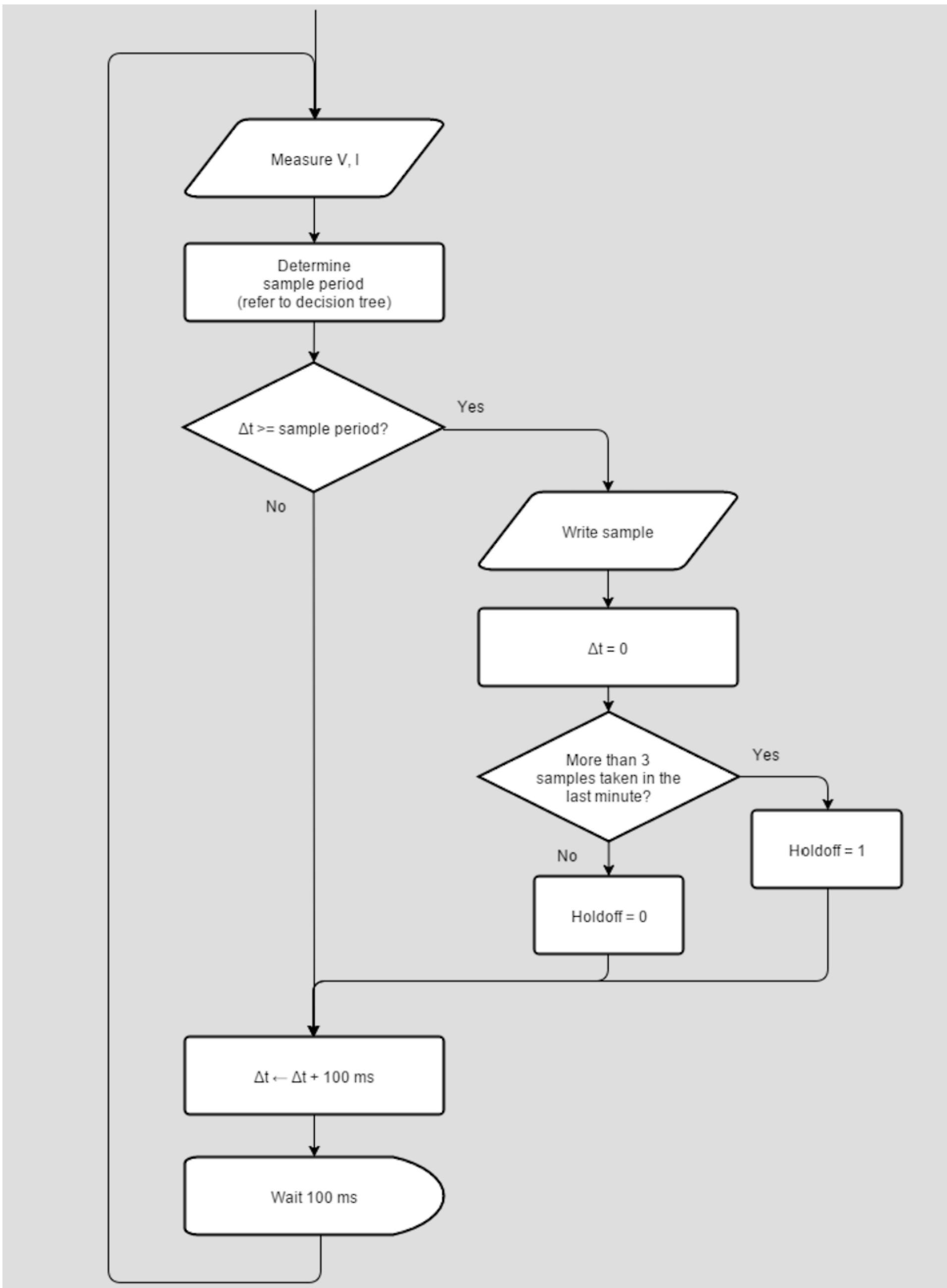

Fig. A- 1 Flow chart for data logging

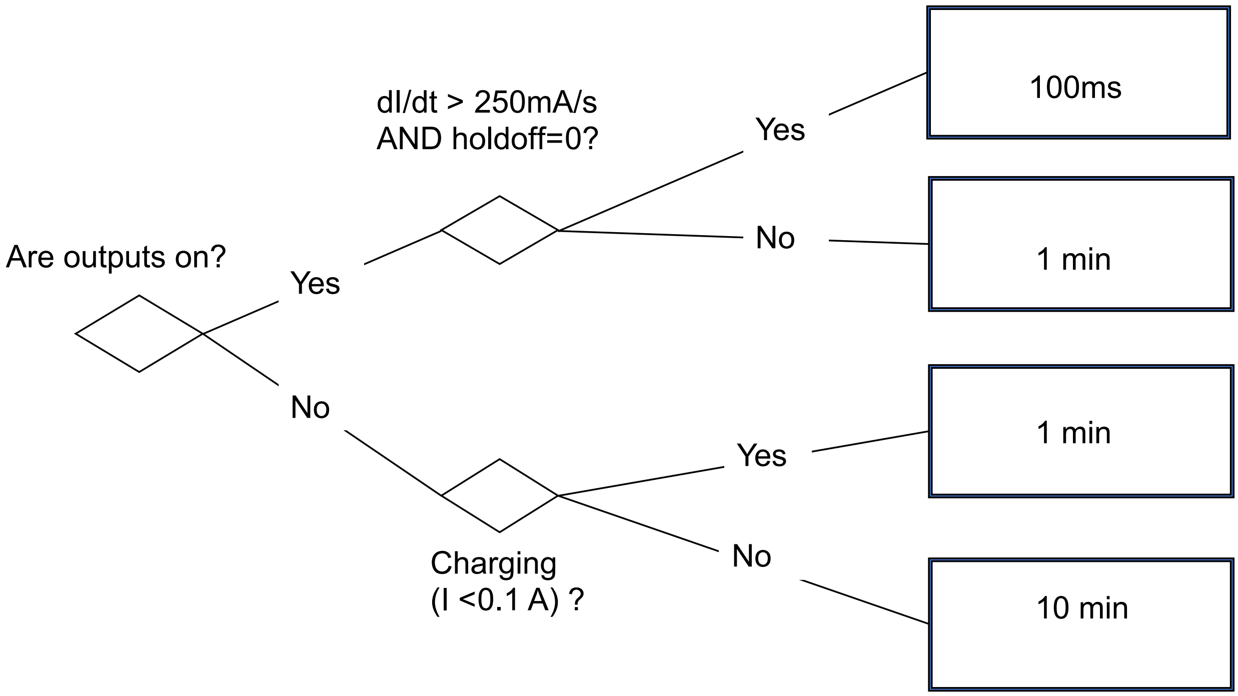

Fig. A- 2 Flow chart to determine sampling period Source: BBOXX Correspondence

6.1.1 Data Cleaning

The raw data contained erroneous readings from the systems, which I omitted from the analysis. I classified entire days as erroneous when:

1) The voltage or current readings were outside the operational limits specified by the product sheet of the SHS provider:
   a) Voltage: 11V< V< 14.6
   b) Current: C<-2.1A or C>0.95A
2) Some timestamps had current readings suggesting charging during the nighttime (19:00-04:59)

The night time scope for our analysis required two parts from a customer's daily load time series. The first part was the evening time series i.e 19:00- 23:59 for the current day and the second part was the early morning time series i.e 00:00 – 05:59 for the next day. The combination of these two parts formed a single night. I filtered through each customer's daily load time series to create a new time series of nights.

Table A- 1 Results of Disaggregation algorithm

<table>
<tr><th>Appliance Use States</th><th colspan="2">Number of Lights</th><th># of observations estimated at that state</th><th>Percentage of Total</th></tr>
<tr><td>0</td><td colspan="2" rowspan="2">0</td><td>4,807,564</td><td>23.04</td></tr>
<tr><td>3.8</td><td>1,053,956</td><td>5.05</td></tr>
<tr><td>1</td><td colspan="2" rowspan="4">1</td><td>4,713,694</td><td>22.59</td></tr>
<tr><td>4.8</td><td>804,502</td><td>3.86</td></tr>
<tr><td>5</td><td>859,517</td><td>4.12</td></tr>
<tr><td>8.8</td><td>62,445</td><td>0.3</td></tr>
<tr><td>2</td><td colspan="2" rowspan="4">2</td><td>3,570,355</td><td>17.11</td></tr>
<tr><td>6</td><td>431,127</td><td>2.07</td></tr>
<tr><td>5.8</td><td>413,818</td><td>1.98</td></tr>
<tr><td>9.8</td><td>28,553</td><td>0.14</td></tr>
<tr><td>3</td><td colspan="2" rowspan="4">3</td><td>2,175,539</td><td>10.43</td></tr>
<tr><td>6.8</td><td>235,386</td><td>1.13</td></tr>
<tr><td>7</td><td>230,964</td><td>1.11</td></tr>
<tr><td>10.8</td><td>7,689</td><td>0.04</td></tr>
<tr><td>8</td><td colspan="2" rowspan="2">4</td><td>104,855</td><td>0.5</td></tr>
<tr><td>11.8</td><td>721</td><td>0</td></tr>
<tr><td>4</td><td rowspan="2">4</td><td rowspan="2">0</td><td>1,253,250</td><td>6.01</td></tr>
<tr><td>7.8</td><td>113,659</td><td>0.54</td></tr>
</table>

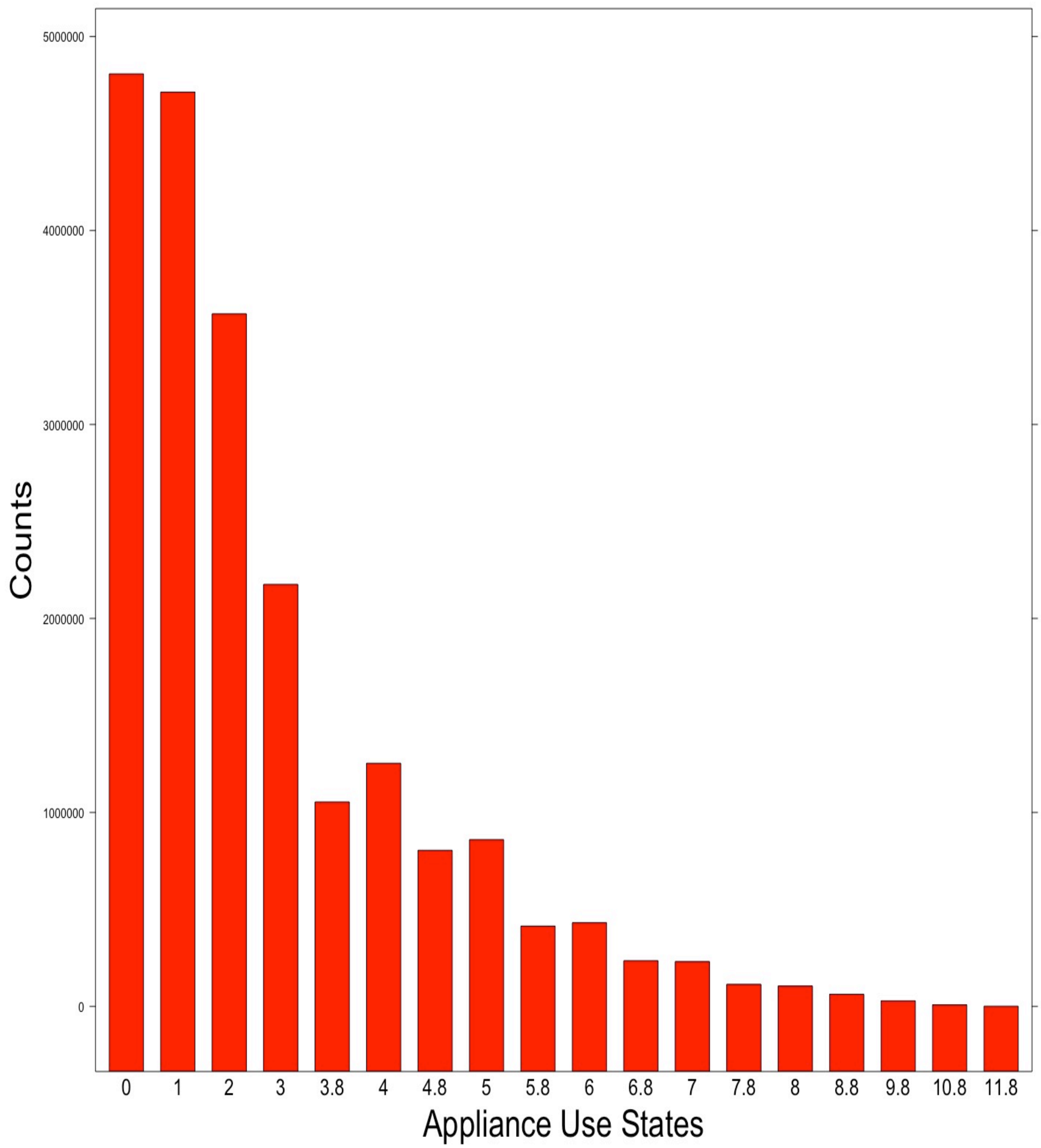

Fig. A- 3Bar-chart shows the frequency of appliance use states in the entire data

Table A- 2 Distribution of Annual Benefits of Solar Options

Elasticity value, ϵ	Median Benefits US$/year						Difference in Annual Benefits US$/ year			
	NetCS (SHS)		Full (SHS)		NetCS (SL)		Diff (L)		Diff (F)	
	High Fig 4a	Low Fig 4b	High Fig 4c	Low Fig 4d	High Fig 4e	Low Fig 4f	High Fig 4g	Low Fig 4h	High Fig 4i	Low Fig 4f
0.2	53 (13,138)	52 (13, 138)	69 (21, 157)	68 (21, 156)	47 (1,133)	46(-71, 130)	0 (0, 34)	12 (1, 121)	0 (0, 206)	12 (0, 218)
0.8	119 (29,282)	113 (36, 262)	135 (50, 300)	128 (45, 279)	90 (3, 200)	78 (-51, 176)	26 (6, 158)	42 (11, 194)	27 (6.9, 210)	44 (12, 232)

Table A- 3 Sensitivity Results for Benefit Cost Ratio Calculations with different elasticity values and discount rates

	Elasticity ,ϵ	5%		15%		25%	
		High	Low	High	Low	High	Low
SHS	0.2	1.1	1.1	1	1	0.9	0.9
	0.8	2	2	1.9	1.8	1.8	1.6
Solar Lanterns	0.2	1.1	1.1	1.1	1	1	1
	0.8	2.1	1.9	2.1	1.8	2	1.8

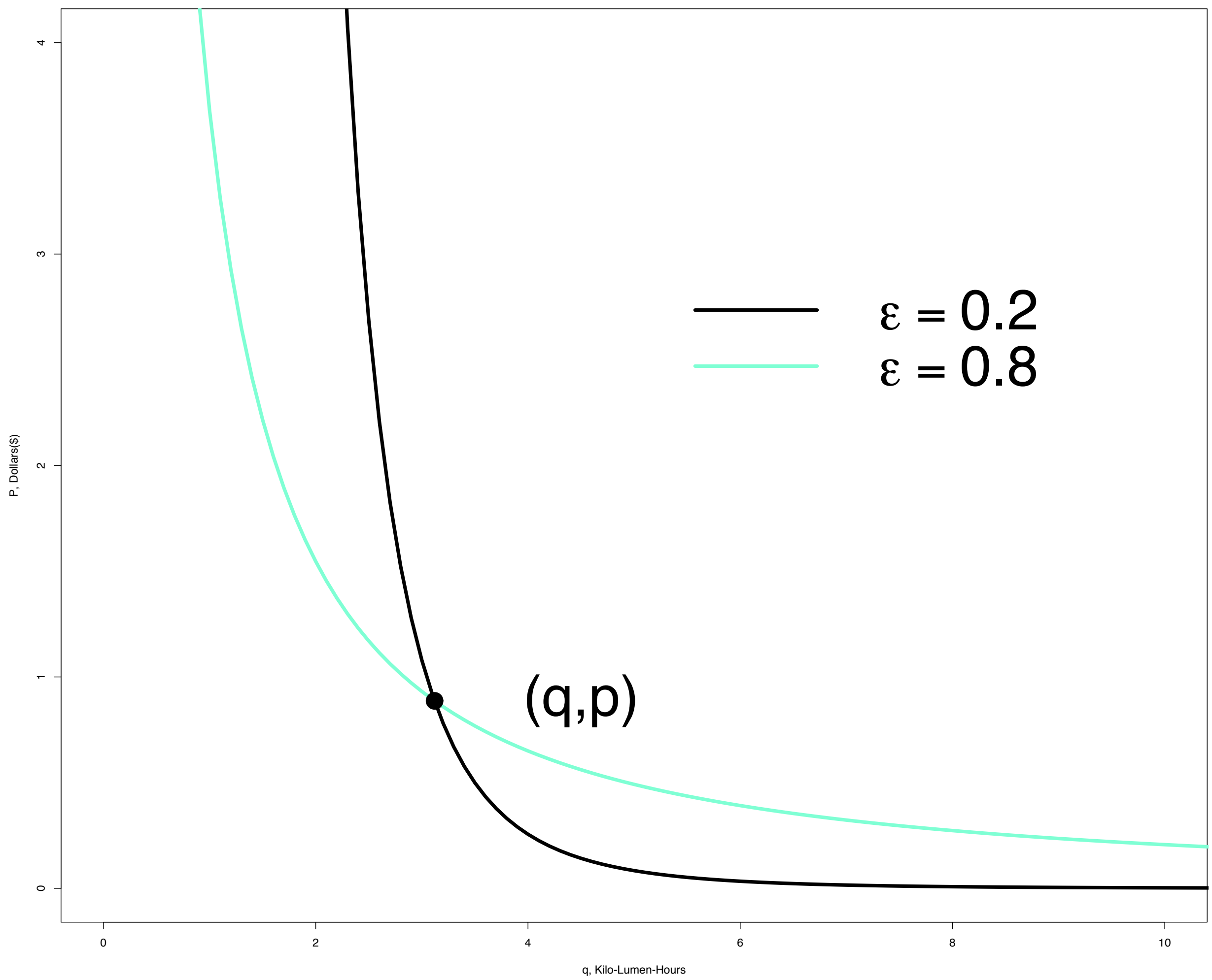

Fig. A- 4 Figure for Demand Curves

The formula used to calculate the net consumer surplus (condition on the solar technology light output) is given by Eq. **Error! No text of specified style in document.**-1

$$NetCS_S = \begin{cases} \dfrac{\varepsilon A^{\frac{1}{\varepsilon}}\left[{q_S}^{1-\frac{1}{\varepsilon}} - {q_K}^{1-\frac{1}{\varepsilon}}\right]}{\varepsilon - 1} + MonthEx, & q_S > q_K \\ \text{MonthEx}, & q_S < q_K \end{cases}$$

(Eq. **Error! No text of specified style in document.**-2)

Table A- 4 Sensitivity Results for percentages of customers with BCR greater or equal to 1 with different elasticity values and discount rates

	Elasticity ,ϵ	5%		15%		25%	
		High	Low	High	Low	High	Low
SHS	0.2	58	58	50	50	44	44
	0.8	92	91	88	86	85	83
Solar Lanterns	0.2	60	57	57	55	54	51
	0.8	89	85	89	84	85	84

Comparison with prior work

Prior work has used different assumptions about a constant daily lighting or has calculated benefits of lighting replacement without considering lighting quality. Here I compare the BCR I obtained using our consumer surplus model based on empirical load data, to the BCR obtained using the fixed-lamp used model reported in [3] (48 lamp-h per day for SHS and 32 lamp-hours a day for solar lanterns)[2] and the expenditure only model from [30], [64]. Compared to the expenditure only model, our results suggest that the SHS would be economically attractive for less than half of the customers, and for just half the customers for solar lanterns. Our model results in similar BCRs values compared to a fixed-lamp availability model, albeit I see slightly higher BCRs when using the higher elasticity value.

Table A- 5 Comparison of BCR ratios to other studies

	Our Model		Fixed Lamp-Use Model		Expenditure Only Model
	$\epsilon = 0.2$	$\epsilon = 0.8$	$\epsilon = 0.2$	$\epsilon = 0.8$	
SHS	1 (51)	2.1 (90)	1.0 (51)	2.4 (93)	0.86 (40)
Solar Lanterns	1.3 (62)	2.3 (93)	1.3 (62)	3 (94)	1.06 (51)

Parenthesis contains the percentage of customers with BCR ratios greater or equal to 1.

[2] SHS: 12 lamph/ lamp; Solar Lanterns: 8 lamph/lamp

7 Appendix B Supporting Information for Economic Assessment of Residential Solar Systems with Battery Storage in Households in Lagos

7.1.1 Grid Tariffs Calculation Beyond

I used the annual grid tariff (g[y]) from the regulated residential tariffs (R2) approved by NERC for Eko Distribution Company – electricity utility for Lagos state [65]. The regulators set the allowable tariffs that can be charged to residential users up until 2024, which is shorter than our model horizon which ends in 2032. I filled the remaining years by assuming a yearly inflation following grid tariff from the last year of the regulated tariff (2024: y = 7) to the model ending year (2032: y =15)

as shown in

$$g[y] = \begin{cases} R2[y], & y \leq 7 \\ \mathrm{R2}[7] \cdot (1 + \mathrm{i})^{y-7}, & 7 < y \leq 15 \end{cases}$$

where R2 is the residential tariff approved by NERC for year y; i is the inflation rate

7.1.2 Grid Parameters for States in ECN Report

The durations of grid service and outages were measured and recorded using a series of watt-meters aggregated at the household's main circuit board. Table B- 1 summarizes the grid parameters from the ECN report [46]which I used as inputs (T_{ON} and T_{OFF}) to generate grid schedules used in the technical model.

Table B- 1 Summary of Grid Parameters

STATE	No of Households	Average Duration of Grid Service in Hours (T-ON)	Average Duration of Grid Outages in Hours (T-OFF)	Average Grid Availability (%)
Abuja	27	4.91 (1.87, 12)	2.91 (1.73, 7.42)	61 (25, 82)
Bauchi	30	2.89 (1.66, 5.05)	4.83 (2.37, 11.9)	39.8 (18.8, 58.9)
Benin	29	6.09 (2.63, 11.2)	4.16 (1.71, 8.75)	58.6 (40.6, 86.1)
Enugu	23	4.82 (2.97, 8.3)	2.68 (1.02, 7.9)	64.6 (38.2, 87.2)

Lagos	26	6.31 (3, 12)	4.44 (1.5, 15)	60.4 (18.9, 85.7)
Sokoto	24	3.40 (1.89, 5.19)	4.44 (1.56, 10.4)	44.6 (15.4, 66)

Minimum and Maximum Values in parenthesis

Table B- 2 Average Diesel & Petrol Prices by States Considered

State	Petrol Price (N/liter)	Diesel Price (N/liter)
Abuja	144.20	224
Bauchi	145	207
Benin	145.25	217
Enugu	145.27	219.09
Lagos	144.44	223.42
Sokoto	145.14	236

Table B- 3 Electricity Tariff for Household under consideration in NGN/kWh

State	Utility	2018	2019	2020	2021	2022	2023	2024
Abuja	Abuja	24.03	20.4	19.69	19.74	19.51	19.4	19.25
Enugu	Enugu	31	22.91	20.99	21.01	20.76	20.63	20.46
Lagos	Eko	20.47	20.06	20.07	20.17	19.98	19.9	19.78
Benin	Benin	31.26	30.98	30.88	27.29	24.49	24.34	24.14
Sokoto	Kaduna	28.75	20.45	19.74	19.75	19.5	19.37	19.21
Bauchi	Jos	30.93	32.05	32.84	33.79	34.76	36.67	29.4

Table B- 4 Technical Summary comparing GD with GD-BP

	Household Reliability (%)		Diesel Consumption in Liters		Grid Consumption in kilo-Watt hours		Peak Hourly Load in kilo-Watt (kW)	
	GD	GD-BP	GD	GD-BP	GD	GD-BP	GD	GD-BP
1	65	80	3705	2563	68619	88210	1.1	2.52
2	72	92	7039	2429		103256		2.53

3	79	94	10066	3218		100808		2.53
4	86	96.7	13334	3999		100780		2.53
5	93	99.5	166689	1694		102840		3.52
6	100	100	20319	1920		102820		3.52

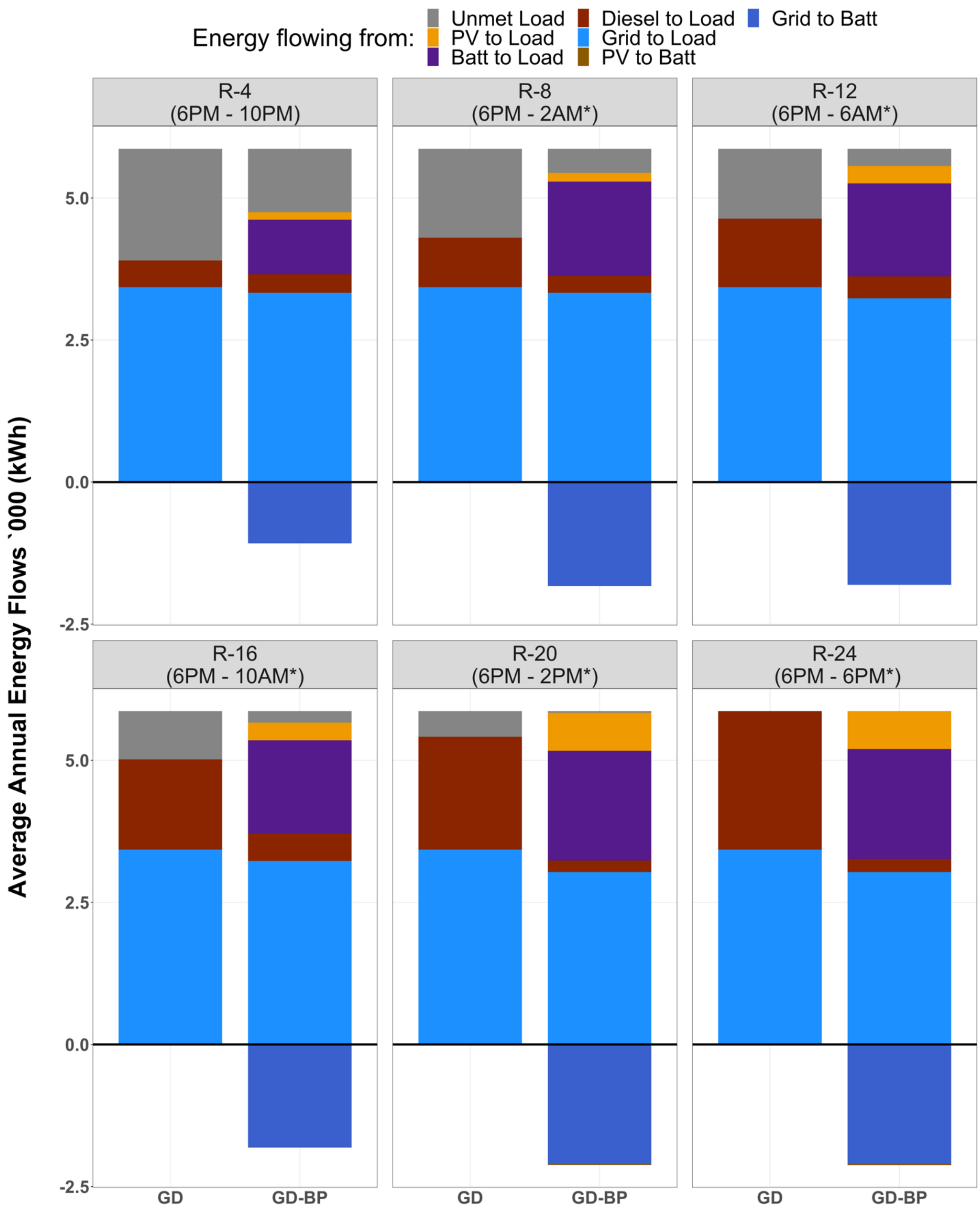

Fig. B- 1 Average Annual Energy Flows for backup generator availability levels considered for Lagos Load profile.

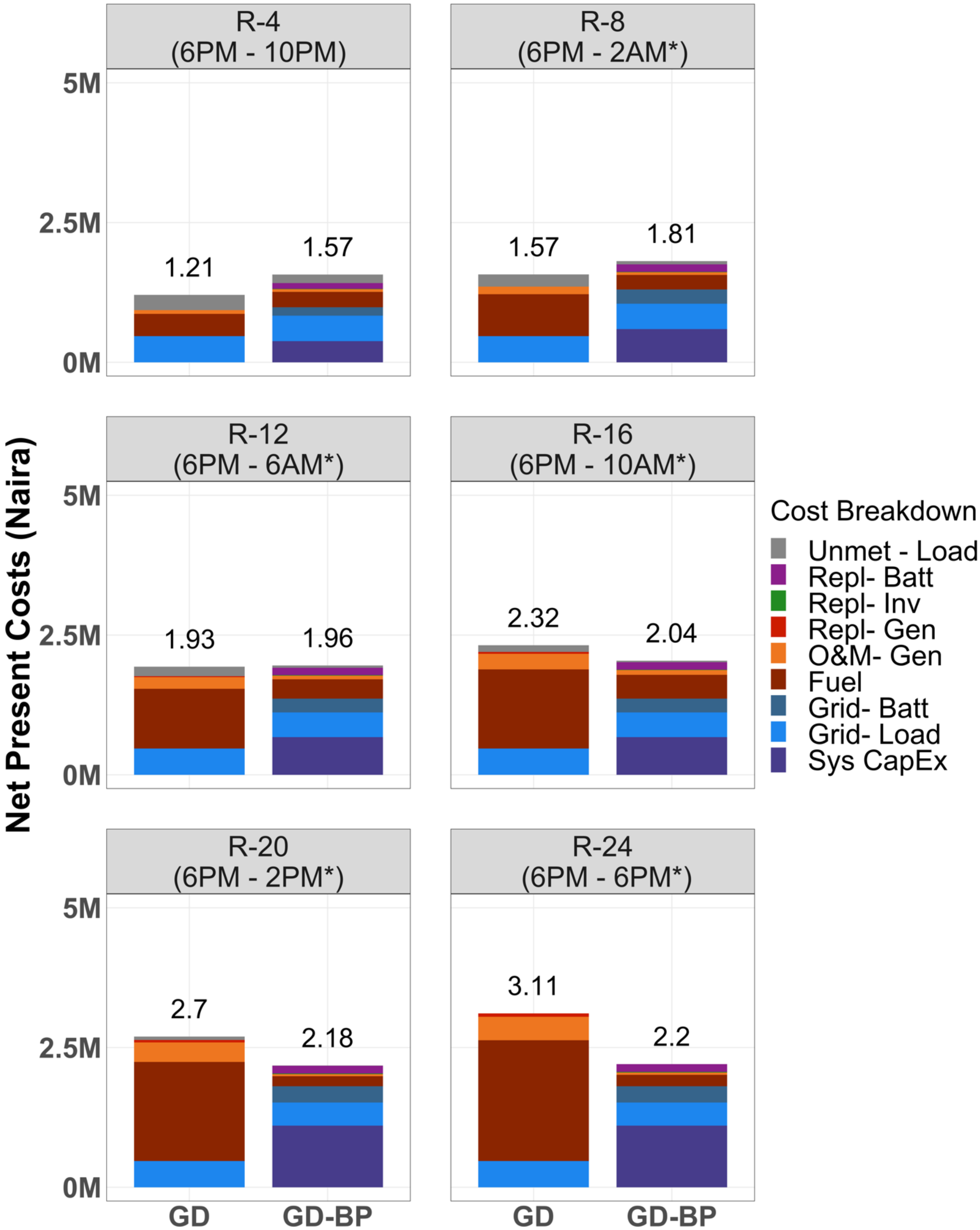

Fig. B- 2 Cost Breakdown of Lagos Households from Eq. (3-8)

Table B- 5 System Sizes for all the grid availability levels

Grid Availability Level (%)	Tier	Grid + Backup Generator +PV+ Battery Storage (GD – PB)			
		Backup Generator Size (kW)	PV Size (kWp)	Battery Storage (#)	Inverter Size (kVA)
26%	R -4	1.5	0.2	2	1.5
	R -8		1.2	6	2.5
	R -12		1	8	2.5
	R -16		1.6	8	3.5
	R -20		2	10	3.5
	R -24		2.6	10	3.5
39%	R -4	1.5	0.2	2	1.5
	R -8		0.8	6	2.5
	R -12		0.8	8	2.5
	R -16		0.8	8	2.5
	R -20		1.4	8	2.5
	R -24		2.4	8	2.5
59%	R -4	1.5		2	1.5
	R -8			6	2.5
	R -12			6	2.5
	R -16			6	2.5
	R -20			6	2.5
	R -24			6	2.5
75%	R -4	1.5	0.2	2	1.5
	R -8		0.2	2	1.5
	R -12		0.2	4	1.5
	R -16		0.2	4	1.5
	R -20		0.6	4	1.5
	R -24		0.6	4	1.5
85%	R -4	1.5	0.2	2	1.5
	R -8		0.2	2	1.5
	R -12		0.2	2	1.5

	R -16		0.2	2	1.5
	R -20		0.4	2	1.5
	R -24		0.2	4	1.5
100%	R -4	1.5	0.2	2	1.5
	R -8		0.2	2	1.5
	R -12		0.2	2	1.5
	R -16		0.2	2	1.5
	R -20		0.2	2	1.5
	R -24		0.2	2	1.5

Table B- 6

Summary of System Sizes for alternative technology options for Lagos household load profile

Tier	Grid + Backup Generator + Battery Storage (GD – BO)			
	Backup Generator Size (kW)	PV Size (kWp)	Battery Storage (#)	Inverter Size (kVA)
R -4	1.5	N/A	2	1.5
R -8			6	2.5
R -12			6	2.5
R -16			6	2.5
R -20			6	2.5
R -24			6	2.5

8 Appendix C Demographic Data for Lagos Households

Table C- 1Demographic Data for Lagos Households

State	Population (million)	Average Household Size	Number of Households (million)	Percentage of Electrified Households (%)	Number of Electrified Households (million)
Abuja	3.56	4.9	0.727	77.7	0.565
Bauchi	6.54	6.8	0.961	29.3	0.281
Edo	4.23	3.8	1.11	82.4	0.918
Enugu	4.4	4	1.11	55.4	0.615
Lagos	12.5	3.8	3.3	99	3.2
Sokoto	4.99	5	0.99	38.9	0.388

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