Techno-economic Analysis on the Development of Off-grid Energy System at Prey Preal, Cambodia

Prepared by

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Abstract

This report serves to perform a techno-economic study using 4 different combinations of off-grid renewable and non-renewable energy model for one unelectrified village of Cambodia with 25 households and 125 people. The simulation is crucial to verify the effectiveness of off-grid power system in rural areas out of reach from the grid system using the available renewable resources in that area. Only biogas and solar energy are considered as the renewable source and diesel as the non-renewable source. HOMER software is used to compute the generator and power module size optimization for each off-grid model. Sensitivity analysis is done by analysing the influence of varying diesel prices on the optimum off-grid model, with the main diesel price at $0.8/litre. The off-grid model with the lowest net present cost will be the victor. From the simulation results, the optimum and most economic off-grid model is the combination of PV modules, biogas generator, diesel generator, AC to DC convertor and batteries, with a net present cost of $658,476, cost of energy of $0.244, renewable fraction of 80.3% and CO_2 emission of 31,717 kg/yr.

Introduction

The development of civilization, urban landscapes, lifestyle enrichment and infrastructures to satisfy the growing population shall increase the electricity demand and this trend remains every year. Electricity is indispensable in the current century, especially when the industry is moving towards the age of digitalization. Big data analysis, cyber security and blockchain technologies consumes enormous electricity to perform necessary computations and decision making. Electricity is needed to power localized sensors and internet routers for online data transmission in Internet of Things (IoT). Aside from the digital trend, factories and their machineries require large power supply to maintain consistent production of commodities and to keep the momentum of the supply chain. In households, humans will rely on primitive methods for cooking, cooling and warming up during a cold without electricity. To summarize everything, the success of mankind in technology and urbanization might not be possible without harnessing electricity as there are many hinderances.

In developed countries, most households are electrified through the grid system. On the other hand, in third-world countries that are still developing, electricity is not accessible for all the populations. The electrified areas received electricity from the grid. Most of this power are generated by conventional method which is the combustion of fossil fuels. Method as such is very harmful to the environment as it emits carbon dioxide, carbon monoxide, sulphuric gases and oxides of nitrogen. Carbon dioxide contributes to greenhouse effect, which leads to global warming. Carbon monoxide gases reduced the air quality and deteriorates the Air Pollution Index (API). Overdosage of carbon monoxide in the blood will reduce human's oxygen intake by the red blood cell, leading to asphyxia or suffocation. Sulphuric gases and nitrogen oxides will form acidic compounds in the atmosphere and these compounds return to the ground as acid rain. Hence, governments are pushing to the vast implementation of renewable energy system to replace the traditional ones. Doing so will not only save the natural resource like fossil fuel from depleting, it will also protect Earth from pollutions.

The problem with some developing countries is the prevalence of unelectrified villages. Electricity is still scarce in such areas. Nevertheless, these villages have better opportunity to adopt renewable energy sources as the grid system is yet to extend over there, provided that the area has adequate renewable resources to be feasible. This allows space management for the construction of renewable energy plants. One of the countries in South-East Asia with huge coverage of unelectrified rural areas is Cambodia.

In Cambodia, the current electrification rates are very low. Out of all the households in Cambodia, only 15% of them received grid-equivalent electricity, as alleged by the Electricity Authority of Cambodia (EAC). [1] Cambodia is still a country where rural households and low-income demography are widespread. Based on a socio-economic survey in 2017, out of all the populations sampled in the survey, roughly 76% of them reside in rural areas. [2] Despite the massive numbers, only 5% of households in rural land received grid-equivalent electricity. On the other hand, 55% of households enjoy such luxury in the city. The rate of rural electrification in Cambodia is lagged as oppose to its neighbours such as Lao and Vietnam in which these countries' electrification rate grew by 30% in the past 10 years. [1] About 90% of the electricity from the grid was used by the capital city of Cambodia, Phnom Penh.

In this report, techno-economic study will be conducted on a few combinations of off-grid hybrid renewable energy system on an unelectrified rural village in Cambodia. The purpose of this report shall highlight the potential of Cambodia's natural resources as a renewable energy source to supply grid-equivalent power to villages with emphasis on the economics of the systems.

Literature Review

The Royal Government of Cambodia (RGC) had acknowledged the issue of poor electricity accessibility in many provinces. Therefore, in 2009, the government devised a master plan to electrified most of the areas in Cambodia. The objective of RGC is to ensure all villages receive grid-equivalent electricity by 2020. Supplies would mean myriad power supplies, be it renewable or non-renewable, that could output a power as great as the that from the grid. By 2030, about three quarters of the rural households should receive grid-equivalent electricity. One of the plans to achieve the goals is grid extension. The grid system will be extended only to selected areas. These areas are known as Potential Area of Grid Extension (PAGE). For a remote area to be considered as PAGE, it must be within a 40km radius from a provincial capital. [1] This also deduce that even with grid extension, not all rural areas will receive electricity from the grid. In such cases, the next best alternative to deliver electricity is through off-grid power system.

Off-grid system is very compatible with the use of renewable energy source. Due to the decentralization of power supply, related parties could use any available resources to generate electricity. Besides that, decentralized power system doesn't require satisfying all load demands in the country, instead, power supply system is deliberately designed for any category of consumer which includes residential, community, commercial and industrial use. This makes off-grid power system more resilient in their purpose. In rural area, off-grid systems stand out more than grid systems. It is unsystematic and not cost-effective to build long transmission line to reach households deep in the jungle or the mountain. In addition, rural area has fewer buildings and infrastructures, making the area suitable to develop off-grid power plants.

The outskirts in Cambodia currently power their households through diesel generator and battery. Some villagers used kerosene to power house lightings. Fortunately, Cambodia has abundant renewable resources for stand-alone power system. Large percentage of Cambodia's agriculture revolves around rice production. In 2011, about 174,000 tons of rice was exported overseas. In 2013, about 4 out of 5 households in Cambodia engaged in agriculture activities. 85% from these households grew crops in agriculture holdings and 81% of the said households grew crops and raised livestock and poultry. [3] Due to the overwhelming agricultural activities, Cambodia could locally produce agricultural waste such as rice husk, rice straw and cassava stem as biomass resources. Rice husk, after combustion, it will form rice husk ash (RHA) and RHA is often disposed in landfill. [4] Little did people know, RHA is rich in amorphous silica, fit for manufacturing silica gel, anode of lithium ion battery, graphene sheets and use for absorbing heavy metals in water. [4] In 2014, an estimated of 372,960 tonnes of RHA can be yield by incinerating all the rice husks in Cambodia. [4] This contributes large amount of amorphous silica and activated carbon for its industrial purpose.

From the statistics, many agricultural holdings practise livestock husbandry. During the time of the conducted census, it was reported that there were two livestock being raised, the large livestock consisting of cattle and buffalo whereas the small livestock consisting of pigs and goats. About 2.7 million of cattle were raised at that time. [3] Chicken and ducks were the most common poultry to be raised in Cambodia. The livestock and poultry will produce manures. In Cambodia, farmers did not use manures that often as a compost as they relied on inorganic fertilizers. Manures are usually left untreated and the stench from the sludge will plague the villagers. Large number of livestock and poultry will contribute enough manures for biomass gasification, producing biogas. The anaerobic digestion of manures in a biodigesters will naturally dispose manures prudently without polluting the environment. At this point, it is certain that biomass resource is adequate in Cambodia, however most biomass (firewood and charcoal) are used in rural households for cooking, instead of generating power.

Next, Cambodia has good solar irradiance. Being close to the Earth's equator, the country has yearly average minimum irradiance of 4.7 kWh/m^2/day per month, good enough for PV modules to generate grid-equivalent solar energy. [1] Wind resources is scarce in Cambodia. The wind has a speed of 2.6 m/s on average. [1]

Although hydro power is feasible with many rivers in Cambodia, the closest river to the area of the case study having potential as a micro hydro dam is Stung Sen river. However, the location of the dam is too far from the village of interest. It will be too costly to build a long power transmission line, so hydro power is not considered for this study.

Now that Cambodia is verified as a potential area for off-grid power systems, it is crucial to evaluate the performance of off-grid systems by reviewing past implementation of hybrid renewable energy systems or HRES. Most technical and economic analysis was done using HOMER software.

In 2016, Bhatt et al. had proposed 4 off-grid HRES comprising different combinations of micro-hydro, photovoltaics, biomass, biogas, diesel and battery for 5 unelectrified villages in Uttarakhand state, India. [5] Besides NPC, COE and RF, the amount of carbon dioxide emission is also one of the criteria in selecting the top 3 off-grid configurations. The proposed HRES was affected by price of diesel fuel and interest rate as the sensitivity variables. From the study, the top 3 configurations consist all the components but with different sizing and their NPC and COE are not far from each other. The author chose the one with the least carbon dioxide emitted.

Later in the same year, Hossain et al. proposed PV, wind, diesel and battery HRES on Berjaya Tioman Resort at the South China Sea, Malaysia. [6] This study is an important evidence that off-grid HRES is applicable for commercial use. The results showed that HRES model gives out less carbon dioxide and more economical than diesel only power systems.

In 2017, Das et al. used HOMER to optimize combinations of biogas generator, wind turbines, photovoltaic modules, diesel generator and lead acid battery for off-grid electricity supply for a village in Bangladesh. [7] The proposed HRES was compared with the incumbent solar home system (SHS) and diesel only system. The paper showed that the optimize hybrid system has greater COE than grid electricity but economically cheaper than SHS. This paper is important to point out the intimidating cost of implementing renewable energy systems. Besides, Yilmaz et al. attempted to optimize the sizing of photovoltaic modules, diesel generators and batteries for a summer house on an isolated island in Kilis, Turkey. [8] The paper shows that off-grid power systems are more cost-effective than extending grid to remote areas.

While most studies used HOMER as an optimization software, Sawle et al. tested 6 different hybrid system combination without the use of HOMER in India. [9] In lieu of that, each combination is modelled as a multi-objective function optimized using 4 techniques namely GA, PSO, BFPSO and TLBO. [9] From the results, TLBO is the best among the 4 algorithms tested. HOMER is a very convenient software for hybrid power system optimization but there are some features in the software which are not customizable. However, this paper could convince researchers to use existing optimization techniques to find the optimum hybrid system while retaining full customizability on their system configurations, parameters and resources.

In 2018, Duman et al. commenced techno-economic study using off-grid photovoltaic modules, wind turbines and fuel cell on regularly and seasonally occupied vacation homes. [10] Two energy storage options are used, battery and hydrogen storage. The COE of the optimum system is lower than that of grid electricity from the previous years but higher than that in the year when the study was conducted.

The study also proved that battery storage costed more reasonably than hydrogen storage. [10] For vacation homes with inconsistent power usage, it is shown from this study how an off-grid system might be a viable option than to connect the homes to the grid. Furthermore, Fodhil et al. compared PSO and HOMER optimization techniques to analyse effectiveness of PV module, diesel and battery HRES for rural electrification in Algeria. [11] From the results, PSO approach is more economical and gives higher photovoltaic penetration than that by HOMER. More importantly, off-grid system supplied energy to the households without power shortage.

In 2019, Javed et al. used GA to optimize a power supply system consisting of photovoltaic module, wind turbine and battery. [12] The loss of power supply probability (LPSP) is used to evaluate the reliability of the system. [12] The results show that off-grid hybrid system can supply enough energy for remote areas. More importantly, GA is more superior than HOMER as it used less computational time to yield a more accurate results, and the user has more authority and flexibility in the development of the hybrid system.

From the past techno-economic studies reviewed, off-grid HRES is proven to be feasible and economical for various scenarios and load demands. Although other optimization techniques might outclass HOMER, HOMER will still be used in this case study. There are many case studies using off-grid hybrid system, none attempt to study the availability of renewable resources in Cambodia and work out the optimum hybrid energy system for the rural areas in the country. As mentioned earlier, Cambodia, being under-developed for most provinces, is rich in agriculture and livestock husbandry activities. Despite that, farmers and government are not utilizing the available resources for the better. The country is largely rural and unelectrified. Currently, it is in the middle of the rural electrification master plan. Nevertheless, preliminary study is needed to ensure off-grid HRES are possible at areas outside PAGE. Hence, techno-economic study in this report is a stepping stone to facilitate RGC for developing off-grid system after the grid extension project is completed, allowing RGC’s quest for a fully electrified Cambodia to be accomplished.

Methodology

There are many unelectrified rural areas in Cambodia and only the capital city, Phnom Penh uses most of the electricity available in the country. Although agriculture and livestock wastes are plenty, not every rural area shares such abundance of resources. It is important to use data from Cambodia Census of Agriculture and Cambodia Socio-economic Surveys for livestock, crops production and demography information. The economics of the off-grid model is determined with HOMER. However, HOMER will only give reasonable and logical results if the data input to it is sensible. Therefore, more scrutiny is made to obtain accurate information on solar irradiance, livestock numbers and agriculture production at the same time able to ensure good approximation on any data should they be unavailable.

The combinations of hybrid systems tested in this case study are:

- PV, Biogas, Diesel & Battery
- PV, Biogas & Battery
- Biogas, Diesel & Battery
- PV, Diesel & Battery

Ideally, the fully renewable off-grid model consisting of PV modules, biogas generator, battery and converter is preferred as the optimum and winning system as this could remove the dependence on diesel generator which contributes to air pollution. Biogas generator will supply power at times where solar energy is insufficient. Battery will store charges and supply electricity during urgent times where the generator is down and no solar is available. Diesel generator is still considered because it can consistently meet the load demand as it isn't intermittent unlike biogas and solar based power system. However, the optimum system simulated with HOMER will be determined with few economics and eco-friendly parameter, such as net present cost, cost of energy, renewable fraction and gaseous emission. Since budget is the main concern, the system with lowest net present cost shall be victorious. Hence, for a fair simulation to be conducted, it is necessary to assess the resources, components, software, load profile and demography for our case study.

Demography of Chosen Village

There are 25 provinces in Cambodia and the chosen province containing valuable renewable resources is Kampong Thom. Kampong Thom has 737 villages and only 203 villages are electrified according to a survey. [13] This study will focus on a village within Kampong Svay, a district of Kampong Thom, known as Prey Preal (latitude: 12˚47.6' N; longitude: 104˚50.1' E). The position of the village is determined with HOMER software location search. Based on a Census in 1998, Kampong Thom has 74,843 people. Assuming 1% population growth rate since the number of rural and urban households grow annually by 1% [2], approximately 92236 populations is expected by 2019. Assuming the populations are distributed equally, and each household has 5 people [3], Prey Preal will have 25 households and 125 people.

Load Profile

Prey Preal is a village containing eateries, churches and sundry shops, not only houses. However, the load demand is based solely on household power consumption. No data is available for the load demand of this small community, estimations are needed. Since the village is rural, no air-conditioner, electric water heater and electric stoves are considered. Only basic home appliances such as television, ceiling fan, fluorescent light, radio, bedroom fan and refrigerator are considered. Since people in the rural area might require access to computer, hence a PC is also accounted for in the load demand. Cambodia has two major seasons, wet and dry seasons. In this study, the power consumption per household for both seasons are equal. Below shows all the electrical appliance and their contributions to the load demand.

Table 1: Power Consumption per day for each household

Electrical Appliance	load each (kW)	No. of units	Duration of used per day (hours)	Power Consumption (kWh)
TV	0.150	1	5	0.750
PC	0.450	2	5	4.500
Ceiling Fan	0.070	3	12	2.520
Fluorescent light	0.040	4	12	1.920
Radio	0.009	1	2	0.018
Bedroom Fan	0.060	4	11	2.640
Refrigerator	0.400	1	24	9.600
Total				21.948

Below shows a detail routine of which electrical appliances are being used at each hour.

Table 2: Usage of Electrical Appliances at each hour per household

Time	Electricity usage activity	Total Power Consumption (kW)
00:00	Bedroom Fan & Refrigerator	0.640
01:00	Bedroom Fan & Refrigerator	0.640
02:00	Bedroom Fan & Refrigerator	0.640
03:00	Bedroom Fan & Refrigerator	0.640
04:00	Bedroom Fan & Refrigerator	0.640
05:00	Bedroom Fan & Refrigerator	0.640
06:00	Bedroom Fan & Refrigerator	0.640
07:00	Bedroom Fan & Refrigerator	0.640
08:00	Bedroom Fan, Refrigerator & Radio	0.649
09:00	Refrigerator	0.400
10:00	Ceiling Fan, Refrigerator, Fluorescent light, PC	1.670
11:00	Ceiling Fan, Refrigerator, Fluorescent light, PC	1.670
12:00	Ceiling Fan, Refrigerator, Fluorescent light, PC	1.670
13:00	Ceiling Fan, Refrigerator, Fluorescent light	0.770
14:00	Ceiling Fan, Refrigerator, Fluorescent light	0.770
15:00	Ceiling Fan, Refrigerator, Fluorescent light	0.770
16:00	Ceiling Fan, Refrigerator, Fluorescent light	0.770
17:00	Ceiling Fan, Refrigerator, Fluorescent light, TV	0.920
18:00	Ceiling Fan, Refrigerator, Fluorescent light, TV	0.920
19:00	Ceiling Fan, Refrigerator, Radio, Fluorescent light, TV	0.929
20:00	Ceiling Fan, Refrigerator, Fluorescent light, TV, PC	1.820
21:00	Ceiling Fan, Refrigerator, Fluorescent light, TV, PC	1.820
22:00	Bedroom Fan & Refrigerator	0.640
23:00	Bedroom Fan & Refrigerator	0.640
	Total Power Consumption	21.948
	Average Total Power Consumption	0.915

From Table 2, the peak demand per household is 1.820 kWh/day from 20:00 to 21:00 which is reasonable as this is the time in which all the family members are within the household unwinding themselves after a long day of work in the farm or plantation.

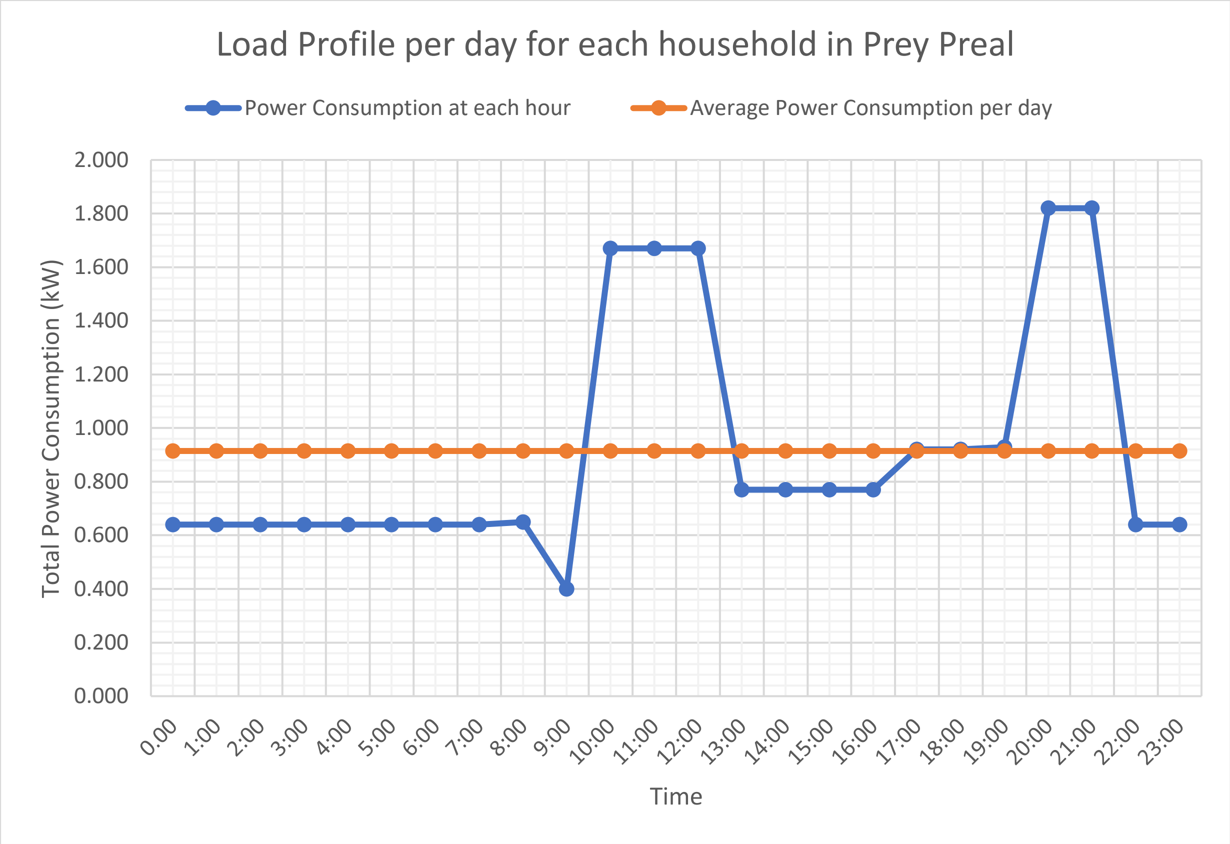

Figure 1: Load Profile per day for each household in Prey Preal

Below shows a heat map illustrating the yearly load profile for each household in Prey Preal.

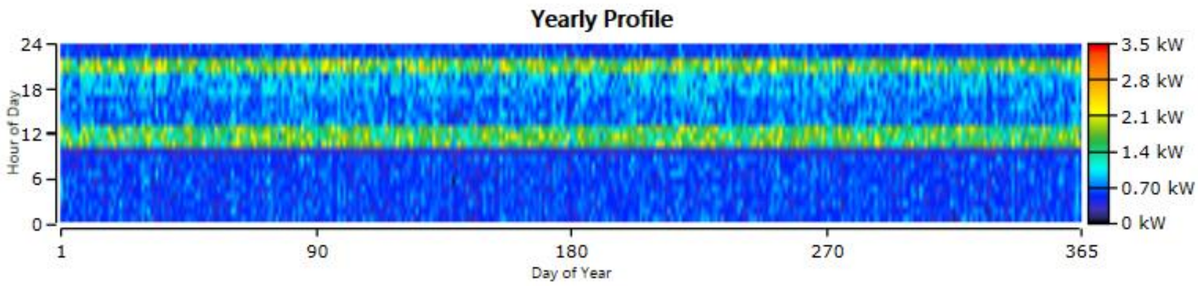

Figure 2: Yearly Load Profile per household in Prey Preal

For the whole village, it is important to consider the load for all 25 households. This would mean an annual average of 548.70 kWh/day, an average total power consumption of 22.9 kW for each day and a peak at 77.89 kW. To ensure variation in the load profile throughout the year, under random variability in HOMER, the day-to-day parameter is set to 10% whereas the timestep is set to 20%. The time step size used is 60 minutes as depicted in Figure 1.

Renewable Energy Resources

Two major renewable energy potential in Cambodia are biogas and solar energy.

1. *Solar Energy:*
   As Cambodia is located close to the Earth's equator, it has good solar irradiance. Based on the coordinates of Prey Preal in the map, the data of the average solar global horizontal irradiance (GHI) per month is extracted from the National Renewable Energy Lab's (NREL) National

Solar Radiation database. [14] The data shows that Prey Preal has a yearly average of 5.46 kWh/m^2/day. This also mean the average peak hour is 5.46 h for the village. Below shows bar chart and table representation of solar GHI with clearness index.

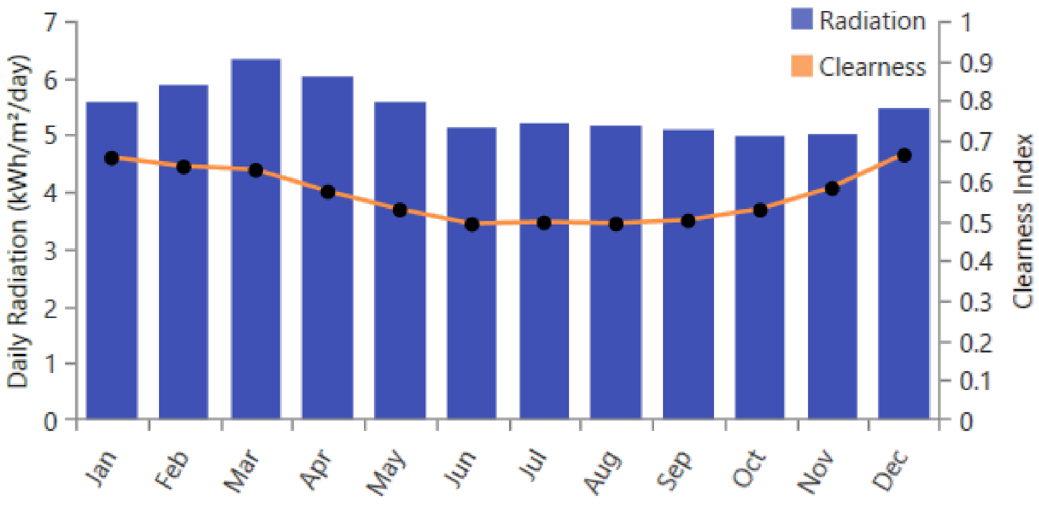

Figure 3: Clearness Index and daily radiation for Prey Preal

Table 3: Detail values of Clearness Index and Solar GHI for Prey Preal

Month	Clearness Index	Daily Radiation (kWh/m^2/day)
January	0.657	5.591
February	0.634	5.891
March	0.626	6.319
April	0.572	6.034
May	0.526	5.574
June	0.49	5.146
July	0.494	5.19
August	0.491	5.157
September	0.499	5.09
October	0.526	4.99
November	0.58	5.027
December	0.664	5.467

2. *Biogas resource:*

Most of the livestock and agriculture data is obtained from the Census of Agriculture in Cambodia. In 2017, the Tonle Sap region had produced 1,777,000 tonnes of rice during the wet season and 489,000 tonnes of rice during the dry season. [2] This region includes Pailin, Otdar Meanchey, Banteay Meanchey, Battambang, Siam Reap, Pursat, Kampong Chhnang and Kampong Thom. In 2013, Kampong Thom contributes 13% of the total aromatic rice crops production for the Tonle Sap region. [3] The statistic will be used as assumption to estimate the amount of rice crops production in Kampong Thom, which is 231,010 tonnes of rice in wet season and 63,570 tonnes of rice in dry season. Assuming all households in every villages in Kampong Thom participated in agriculture holdings and own equal share of rice production, Prey Preal will produce 313 tonnes of rice in wet season and 86 tonnes of rice in dry season. Rice production will generate rice husk and rice straw for biomass gasification. According to a study, 1 kg of paddy can yield approximately 0.41 kg to 3.96 kg of rice straw and about 20% – 33% of each kilos of paddy belongs to the rice husk. [4] In this study, 1 kg of rice can yield about 0.28 kg of rice husk and 1.05 kg of rice straw. For livestock, it is reported in 2013 that Kampong Thom has 47,000 buffaloes, 195,000 cattle, 1.6 million chickens and 270,000 ducks. [3] By dividing the number of animals equally among each village, livestock in Prey Preal can be determined. It is estimated that 15 kg/day of manure is produced by each cattle, 24 kg/day of manure from each buffalo and 0.018 kg/day from each poultry. All poultry manures are assumed to have desired carbon to nitrogen ratio which is about 25 – 30, fit for anaerobic digestion in the biodigesters. Below table shows the amount of manure and rice waste the village can produce in a day:

Table 4: Details on the amount of animal manure and agriculture waste

Waste type	Number of heads in a village (livestock only)	Amount (tonnes/day)	
		wet season	dry season
Agriculture Waste:			
Rice Straw		1.827	0.504
Rice Husk		0.487	0.134
Animal Manure:			
Cattle	265	3.975	3.975
Buffalo	64	1.536	1.536
Chicken	2171	0.039	0.039
Duck	366	0.007	0.007
Total		7.871	6.195

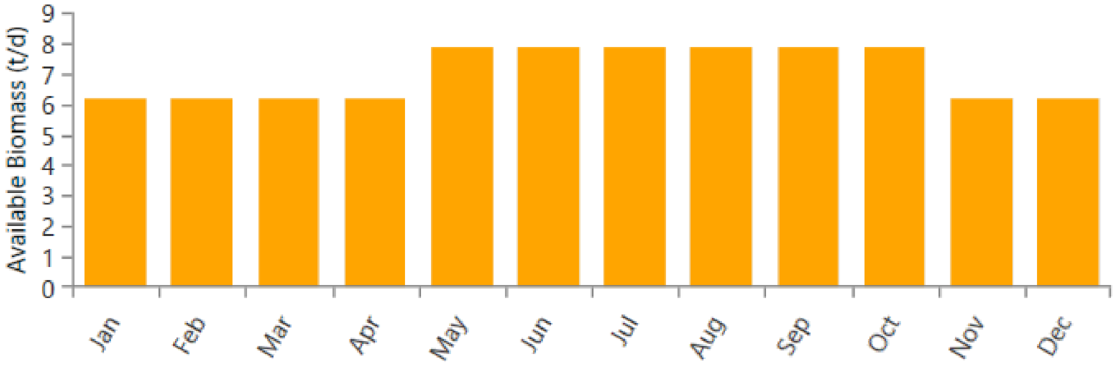

Figure 4: Bar chart representing the available biomass for each month

When evaluating the amount of rice husk and rice straw, it is important to consider wet and dry seasons taking 6 months duration respectively and each month has 30 days. From number of animals shown in Table 4, each household on average should have 10.6 cattle, 2.56 buffaloes, 86.84 chickens and 14.64 ducks. For an agriculture holding, this value is reasonable. The biogas potential is also estimated for each manure type, with large ruminants (buffalo) producing 0.6 $m^3kg^{-1}TS$ of biogas, small ruminants producing 0.4 $m^3kg^{-1}TS$ of biogas and poultry producing 0.8 $m^3kg^{-1}TS$ of biogas. [15] All manures are assumed 100% total solid content (TS). Density of biogas is 1.15 kg/m^3. Calorific value of biogas is taken as 6 kWh/m^3, where 1 kWh = 3.6 MJ.

Hence the calorific value of biogas for the manure is 21.6 MJ/m^3. [15] The product of this calorific value and each amount of biogas produced by each type of livestock will give the estimated Lower Heating Value (LHV). The LHV of rice straw and rice husk are 14 MJ/kg and 12.85 MJ/kg. [16] Below shows a table of all the LHV values:

Table 5: Biomass resource and their LHV values

Waste Type	LHV (MJ/kg)
Livestock manure:	
Cattle	8.64
Buffalo	12.96
Chicken or Duck	17.28
Agriculture waste:	
Rice Husk	12.85
Rice Straw	14.00
Average	13.15

Average value of LHV is needed because HOMER restricts more than one biomass resource, so only one LHV value can be inputted. Gasification ratio is 0.7 and carbon content in each biomass resources is assumed 10%. Cost for livestock manure is USD $20.00/tonne. Cost for rice husk and rice straw is USD $5.00/tonne, as it was reported that a local Cambodian rice husk plant, SOMA Group paid this amount for one tonne of rice husk from the farmers in Kampong Thom. [17] Below summarizes all the cost for each waste:

Table 6: Cost of waste per tonne

Waste Type	Amount (tonne/day)		Cost (USD $/day)	
	Wet Season	Dry season	Wet Season	Dry Season
Livestock manure:				
Cattle	3.975	3.975	79.5	79.5
Buffalo	1.536	1.536	30.72	30.72
Chicken	0.039	0.039	0.78	0.78
Duck	0.007	0.007	0.14	0.14
Agriculture waste:				
Rice Husk	0.487	0.504	2.435	2.52
Rice Straw	1.827	0.134	9.135	0.67
Total	7.871	6.195	122.71	114.33
Cost per tonne (USD $/tonne)			15.59	18.46
Average price (USD $/tonne)			17.02	

Average price of biomass resources is USD $17.02/tonne.

HOMER

Hybrid Optimization Model for Electric Renewable (HOMER) is suitable to perform techno-economic analysis, sensitivity analysis and optimization on grid-connected or non-grid connected power systems. By choosing a suitable case study, HOMER takes in meteorological data, load profile, sensitivity variables and economic parameters to optimize a given power supply configuration. It automatically deduces the most optimum and cost-effective power supply configuration according to the lowest net present cost. Users can compare different configurations easily. Net present cost (NPC) can be calculated as shown below [5]:

$$\mathrm{NPC} = \sum_{t=0}^{N} (\mathrm{Cap}_t + \mathrm{O\&M}_t + R_t + F_t - S_t)$$

N is the total duration of the project (in years) and t is the year within the project duration. Cap_t is the capital cost in that present year, $O\&M_t$ is the cost of operation and maintenance in that present year, R_t is the replacement cost in that present year, F_t is the fuel cost in that present year and S_t is the amount that could be salvaged in that year.

There are more equations used in HOMER. As NPC is the objective function to decide on the optimum off-grid power supply configurations, only this equation will be covered here.

Economic Parameters

Table 7 shows the economic parameters chosen for the study. Cost penalty for the emission of harmful gases are omitted.

Table 7: Economics parameters and the value assigned

Parameters	Value
Nominal discount rate (%)	8.00
Expected inflation rate (%)	2.40
Project lifetime (years)	25
System fixed capital cost ($)	0.00
System fixed O&M cost ($/year)	0.00
Capacity shortage penalty ($/kWh)	0.00

Components

This section will present all the components used in every off-grid configuration. Important parameters such as capital cost, replacement cost, O&M cost, component sizing and type of components will be highlighted.

a. *Diesel Generator*

   The chosen generator is a generic medium size genset with the option of customizing the size of the genset. It has a capital cost of USD $400.00/kW, replacement cost of USD $400.00/kW and O&M cost of USD $0.02 for each operation hour. It has a lifetime of 15,000 hours and a minimum load ratio of 25%. Combined Heat and Power (CHP) effect is ignored hence the CHP heat recovery ratio is set to 0%. The generator shall output AC current. The generator uses a linear fuel curve with a reference generator capacity of 100, intercept coefficient of 0.028 (litre/hour/kW rated) and slope of 0.2530 (litre/hour/kW output).

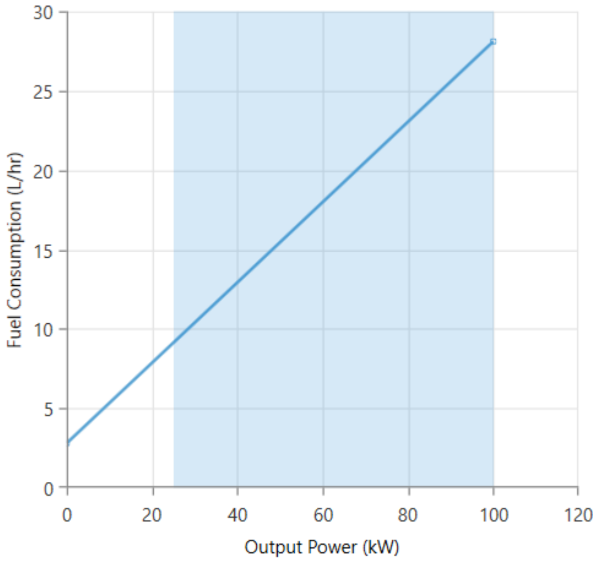

Figure 5: Fuel curve for diesel generator

Below also shows the efficiency curve for the generator:

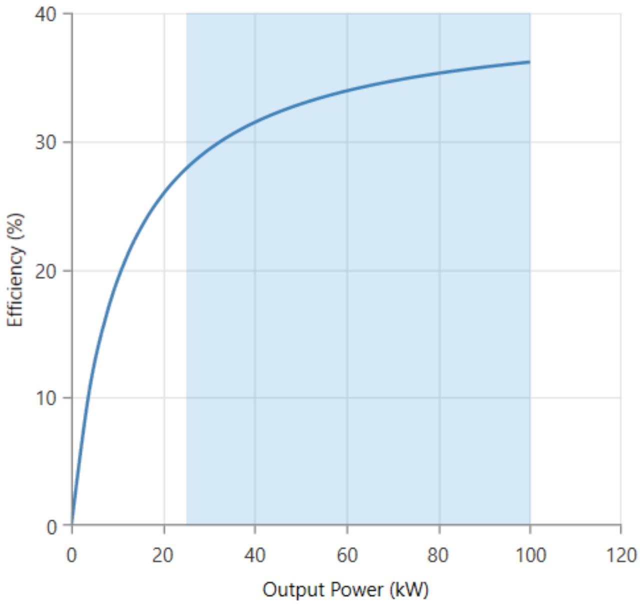

Figure 6: Efficiency curve of diesel generator

The generator runs on diesel fuel. The diesel properties and the generator emissions are depicted in Table 8:

Table 8: Details of emission from generator and diesel fuel properties

Generator details	Value
Fuel properties	
Lower Heating Value (MJ/kg)	43.2
Density (kg/m3)	820
Carbon Content (%)	88
Sulphur Content (%)	0.4
Emissions	
Carbon Monoxide (g/litre of fuel)	17.794
Unburned Hydrocarbon (g/litre of fuel)	0.72
Particulate Matter (g/litre of fuel)	0.0712
Proportion of fuel sulphur converted to PM (%)	2.2
Nitrogen Oxide (g/litre of fuel)	1.4235

The size of the diesel generator has a range from 0 kW to 100 kW with 20 kW as step size.

b. *PV Module:*

The generic flat plate PV is used to harvest solar energy. It has size ranging from 0 kW to 100 kW with 20 kW as step size. Table 9 shows the specifications of the PV module.

Table 9: PV Specifications in HOMER

PV Specifications	Value
Capital Cost (USD $/kW)	2,500.00
Replacement Cost (USD $/kW)	2,000.00
O&M cost (USD $/year)	10.00
Lifetime (year)	25
Derating Factor (%)	80
Efficiency at STC (%)	18
Rated Capacity (kW)	100
Tracking	No
Ground Reflectance (%)	20

The efficiency of the PV module is also temperature-dependant. Every 1℃ increase in temperature will reduce the efficiency by 0.5%. The nominal operating temperature of the PV module is 47℃. The ambient temperature in Prey Preal is obtained from NASA Surface Meteorology and Solar Energy Database. [18] The annual mean temperature in Prey Preal is 26.22℃.

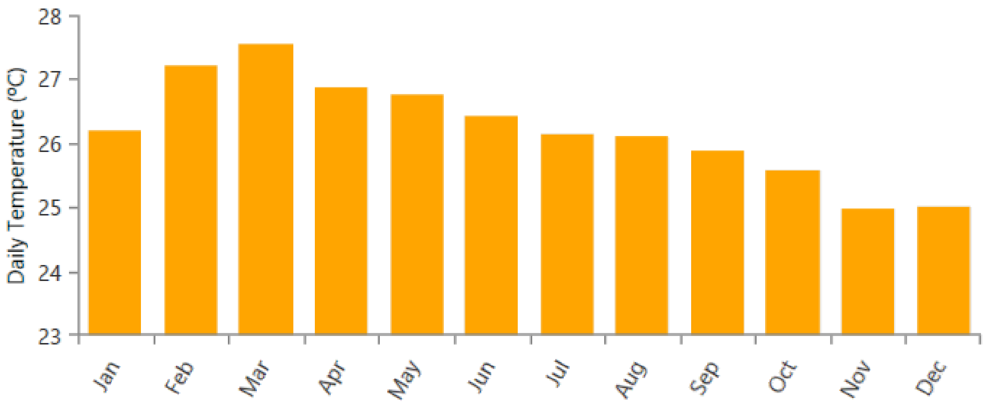

Figure 7: Ambient Temperature in Prey Preal throughout the year

c. *Biogas Generator*

Generic biogas generator of customizable size is chosen for this study. Size of this generator is ranged between 0 kW to 100 kW with 20 kW as step size. It uses the available biomass resources to produce required biogas for electricity generation. Table 10 shows the specification of this generator.

Table 10: Biogas generator specifications

Biogas generator Specifications	Value
Capital Cost (USD $/kW)	3,000.00
Replacement Cost (USD $/kW)	1,250.00
O&M cost (USD $/operation hour)	0.10
Lifetime (year)	25
Minimum Load Ratio (%)	50
CHP heat recovery ratio (%)	0
Minimum Runtime (Minutes)	0
Emissions	
Carbon Monoxide (g/litre of fuel)	2
Unburned Hydrocarbon (g/litre of fuel)	0
Particulate Matter (g/litre of fuel)	0
Proportion of fuel sulphur converted to PM (%)	0
Nitrogen Oxide (g/litre of fuel)	1.25

A linear fuel curve is also used for the biogas generator. The reference generator capacity is 100. Intercept coefficient is 0.100 (litre/hour/kW rated) and slope of 2.00 (litre/hour/kW output). Figure 8 and 9 shows the fuel curve and efficiency curve for the biogas generator.

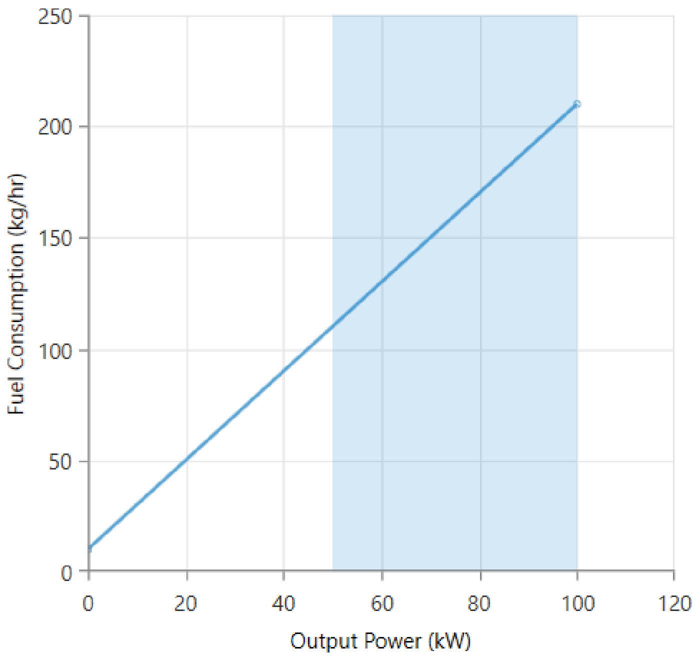

Figure 8: Fuel curve for biogas generator

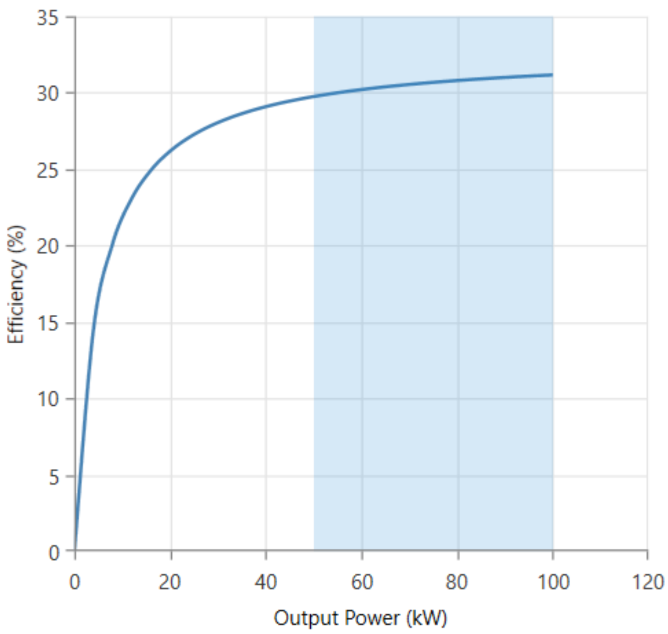

Figure 9: Efficiency curve for biogas generator

d. *Battery*

Lead Acid battery will be used as backup source when renewable energy is unavailable. The size or the number of batteries is ranged from 0 to 300 with a step size of 50. Table 11 presents the specification of this battery.

Table 11: Specification of lead acid battery

Biogas generator Specifications	Value
Capital Cost (USD $/unit)	300.00
Replacement Cost (USD $/unit)	300.00
O&M cost (USD $/year)	10.00
Lifetime (year)	10
Throughput (kWh)	800
Initial State of Charge (%)	100
Minimum State of Charge (%)	40
Nominal Voltage (V)	12
Nominal Capacity (kWh)	1
Maximum Capacity (Ah)	83.4
Capacity ratio	0.403
Rate constant (1/hour)	0.827
Roundtrip efficiency (%)	80
Maximum Charge Current (A)	16.7
Maximum Discharge Current (A)	24.3
Maximum Charge Rate (A/Ah)	1

e. *Converter*

An AC to DC converter is needed to rectify generator electricity to be stored in the battery. Table 12 shall present the specification of the converter. The size of converter is ranged between 0 kW to 100 kW with 20 kW as step size.

Table 12: Converter Specifications

Converter Specifications	Value
Capital Cost (USD $/kW)	300.00
Replacement Cost (USD $/kW)	300.00
O&M cost (USD $/year)	0.00
Inverter Lifetime (year)	15
Inverter Efficiency (%)	95
Rectifier Relative Capacity (%)	100
Rectifier Efficiency (%)	95

Dispatch Strategy

In HOMER, there are two types of power supply controller, which are load following (LF) and cycle charging (CC). For LF, the generator only supplies enough energy for the net load and any operating reserve requirements. Battery will be charged by renewable sources and any excess from forcing generator to meet its minimum load constraint. For CC, battery is charged to the maximum possible level when generator is operated to meet the net load. In this case, net load refers to remaining load that cannot be satisfy by renewable sources. In this report, both LF and CC strategies are selected. HOMER will suggest the best controller in the optimum configuration.

Off-grid Model Configuration
4 different configurations are proposed.

- Configuration A:

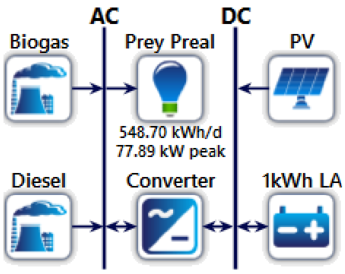

Figure 10: PV, Biogas, Diesel, Battery, Converter

- Configuration B:

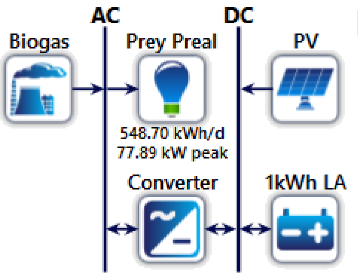

Figure 11: PV, Biogas, Battery, Converter

- Configuration C:

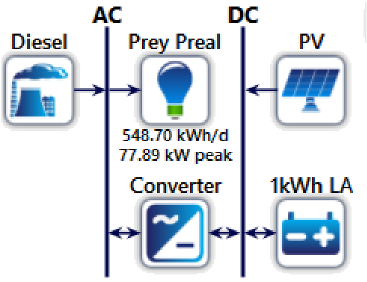

Figure 12: PV, Diesel, Battery, Converter

- Configuration D:

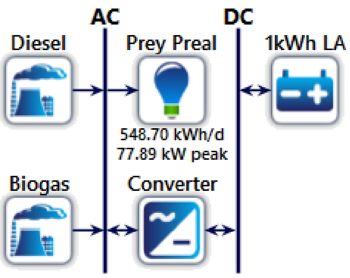

Figure 13: Biogas, Diesel, Battery, Converter

Analysis and Discussion
This section shall assess each configuration according to HOMER simulation. The sensitivity variables used for all configuration is diesel price, which is varied from USD $0.80/litre to USD $1.20/litre with a step size of USD $0.10/litre. The main diesel fuel price for all configurations is USD $0.80/litre.

Configuration A – PV/Biogas/Diesel/Battery/Converter
Table 13 shows the results for this configuration.

Table 13: Economics of Configuration A

Diesel price ($/litre)	PV (kW)	Biogas (kW)	Diesel (kW)	Lead Acid (Qt)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/year)	RF (%)
0.80	20.0	20.0	40.0	50	20.0	CC	658,476	0.244	38,014	80.3
0.90	20.0	20.0	40.0	50	20.0	CC	674,282	0.250	39,189	80.9
1.00	40.0	20.0	20.0	150	40.0	CC	691,737	0.257	34,689	88.4
1.10	40.0	20.0	20.0	150	40.0	CC	698,567	0.259	35,197	88.6
1.20	40.0	20.0	20.0	150	40.0	CC	683,966	0.254	34,111	88.2

Table 14: Cost Summary for Configuration A for diesel price of $0.80/litre

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Lead Acid	15,000.00	15,684.87	6,727.47	0.00	140.07	37,272.27
Biogas Genset	60,000.00	0.00	222,302.48	94,684.29	376.22	376,610.55
Flat Plate PV	50,000.00	0.00	2,690.99	0.00	0.00	52,690.99
Diesel Genset	16,000.00	21,605.71	20,020.95	129,908.68	3,804.24	183,731.09
Converter	6,000.00	2,699.57	0.00	0.00	528.37	8,171.20
System	147,000.00	39,990.15	251,741.89	224592.97	4,848.90	658,476.10

Figure 14 shows the annual contribution of each power modules on satisfying the load demand for Configuration A.

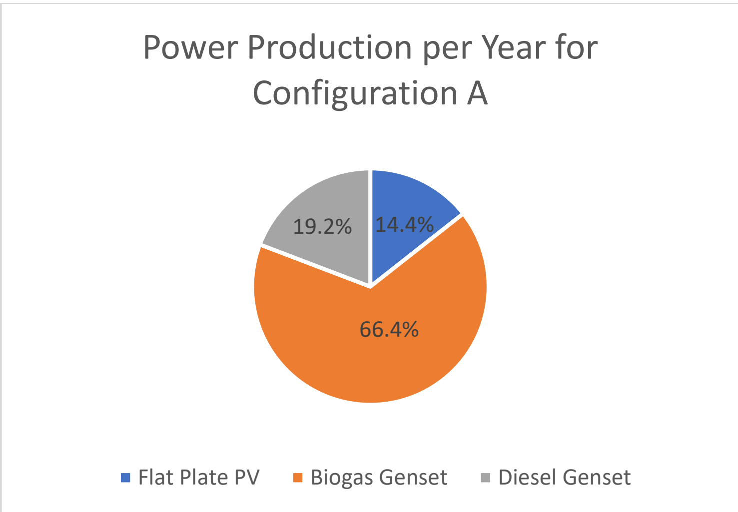

Figure 14: Contribution of power output per year by each power module for Configuration A

In Configuration A, biogas generator contributes the most power throughout the year (about 136,451 kWh/year). Diesel genset contributes 39,469 kWh/year. PV only contributes 29,526 kWh/year.

Table 15: Electricity Production Evaluation for Configuration A

Quantity	kWh/year	(%)
Excess Electricity	2,396	1.17
Unmet Electric Load	12.6	0.0063
Capacity Shortage	89.8	0.0448

Only a small and insignificant amount of electric load is unmet. Below shows the power output of PV, diesel generator and biogas generator per day.

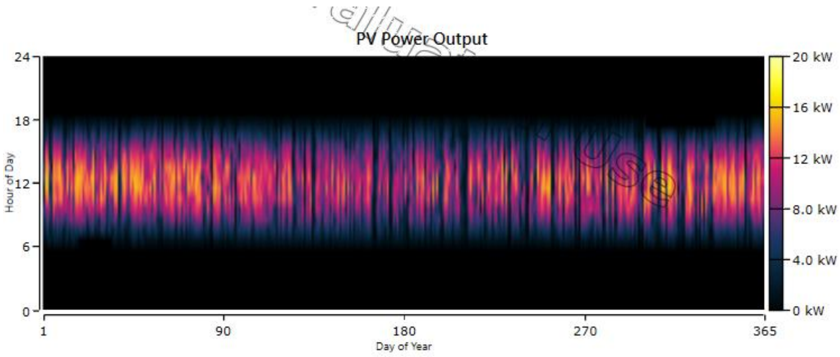

Figure 15: PV Power Output per day for Configuration A

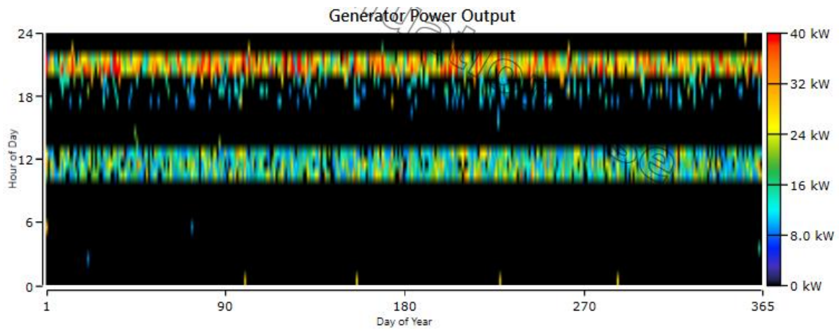

Figure 16: Diesel Genset Power Output per day for Configuration A

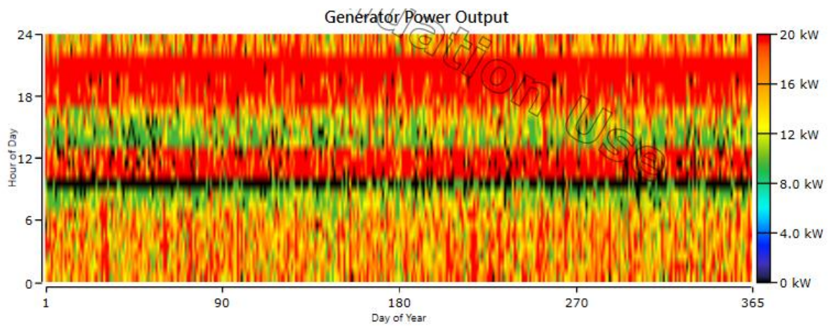

Figure 17: Biogas Genset Power Output per day for Configuration A

For Configuration A, PV is active when there is sunlight from 06:00 to 18:00, with the peak power at 12.00 p.m. Biogas contributes the most power with the highest at the two peaks in the load profile. Diesel generator mainly supply supporting power during the peak load.

Total biomass usage annually is 413 tonnes. Total diesel fuel usage annually is 12,069 litres. Table 16 shows the emissions produced from Configuration A.

Table 16: Emission types and amount per year for Configuration A

Quantity	Value (kg/year)
Carbon Dioxide	31,717
Carbon Monoxide	216
Unburned Hydrocarbons	8.69
Particulate Matter	0.859
Sulphur Dioxide	77.4
Nitrogen Oxides	17.7

Configuration B – PV/Biogas/Battery/Converter

Table 17 shows the result of this configuration. Since diesel fuel is not involved, there is no sensitivity analysis here. Only the winning system is presented.

Table 17: Economics of Configuration B

PV (kW)	Biogas (kW)	Lead Acid (Qt)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/year)	RF (%)
80.0	20.0	250	80.0	CC	768,202	0.285	30,413	100

Table 18: Cost Summary of Configuration B

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Lead Acid	75,000.00	115,245.23	33,637.34	0.00	5,033.59	218,848.98
Biogas Genset	60,000.00	0.00	165,926.29	81,933.38	1,955.74	305,903.93
Flat Plate PV	200,000.00	0.00	10,763.95	0.00	0.00	210,763.95
Converter	24,000.00	10,798.27	0.00	0.00	2,113.46	32,684.81
System	359,000.00	126,043.50	210,327.58	81933.38	9,102.79	768,201.67

Figure 18 shows a pie chart depicting the contributions of each power module for annual power output.

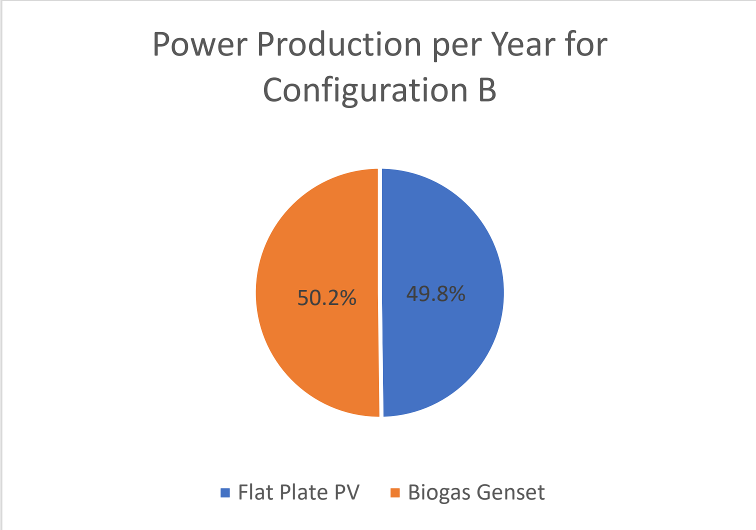

Figure 18: Contribution of Power output by each power module in Configuration B

In configuration B, biogas genset still output the most power annually which is about 119,058 kWh/year, whereas PV module output about 118,105 kWh/year. Regardless, the load is divided almost equally among both power modules.

Table 19: Electricity Production Evaluation for Configuration B

Quantity	kWh/year	(%)
Excess Electricity	24,632	10.4
Unmet Electric Load	121	0.0604
Capacity Shortage	198	0.0989

From Table 19 it is shown that the unmet electric load is insignificant. This shows that even without diesel generator or grid system, Cambodia's renewable resources alone is adequate to yield energy to power a village. Below shows the PV and biogas genset power output per day.

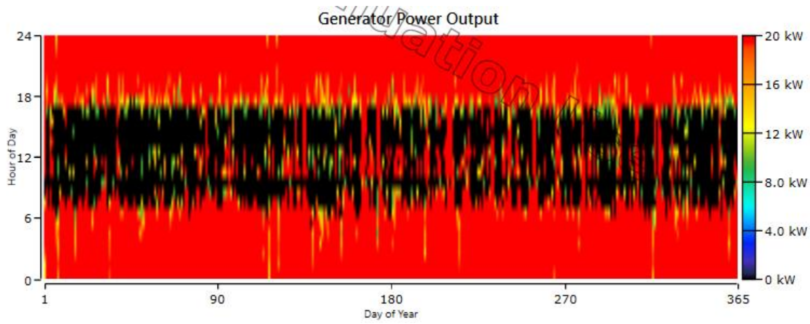

Figure 19: Biogas power output per day for Configuration B

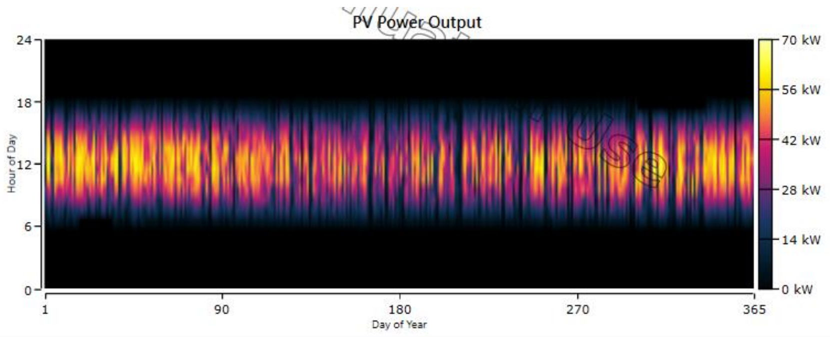

Figure 20: PV power output per day for Configuration B

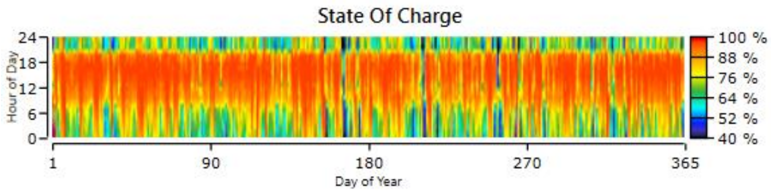

Figure 21: State of charge of the lead acid battery

From Figure 19 and Figure 20, it is obvious that both biogas genset and PV modules are working in synergy every day. Under good solar irradiance, PV is the main energy yielder whereas biogas generator will take charge during the PV module's down time. During peak sunlight, PV module is responsible for the charging of the lead acid batteries. The batteries then discharge to support the biogas generator to satisfy the load demand when solar irradiance is unavailable. About 358 tonnes of biomass resources is consumed per year for Configuration B. Below shows the emission produced by Configuration B.

Table 20: Emissions type and amount by Configuration B

Quantity	Value (kg/year)
Carbon Dioxide	130
Carbon Monoxide	0.716
Unburned Hydrocarbons	0
Particulate Matter	0
Sulphur Dioxide	0
Nitrogen Oxides	0.447

Configuration C – PV/Diesel/Battery/Converter

Table 21 shows the result for this configuration.

Table 21: Economics of Configuration C

Diesel price ($/litre)	PV (kW)	Diesel (kW)	Lead Acid (Qt)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/year)	RF (%)
0.80	60.0	40.0	150	40.0	CC	892,955	0.331	49,792	32.5
0.90	60.0	40.0	150	40.0	CC	947,741	0.352	53,864	32.5
1.00	80.0	20.0	300	60.0	CC	996,949	0.370	50,610	40.8
1.10	80.0	20.0	300	60.0	CC	1.04M	0.387	53,939	40.8
1.20	80.0	20.0	300	60.0	CC	1.09M	0.403	57,267	40.8

Table 22: Cost Summary for Configuration C

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Lead Acid	45,000.00	41,936.99	20,182.41	0.00	5,944.12	101,175.28
Flat Plate PV	150,000.00	0.00	8,072.96	0.00	0.00	158,072.96
Diesel Genset	16,000.00	86,341.77	69,642.76	446,295.37	915.83	617,364.06
Converter	12,000.00	5,399.14	0.00	0.00	1,056.73	16,342.40
System	223,000.00	133,677.90	97,898.13	446295.37	7,916.68	892,954.70

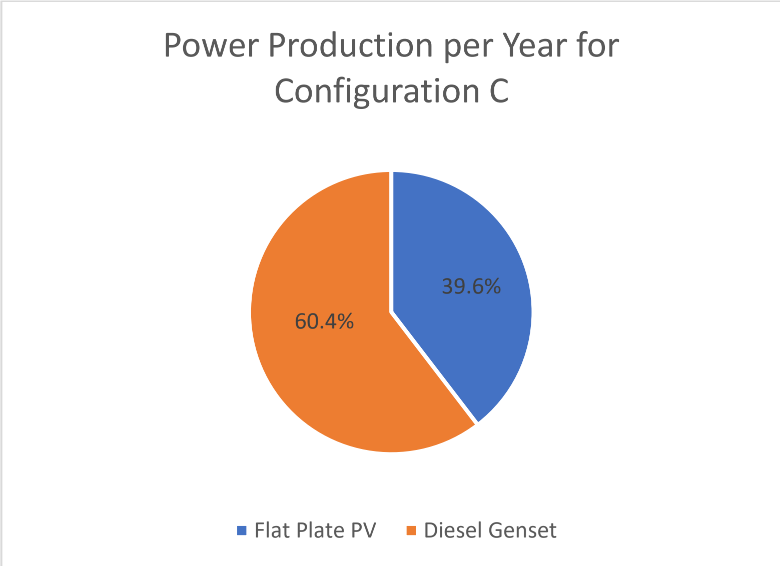

Figure 22: Contribution of power output for each power module in Configuration C

Diesel generator contributes 135,240 kWh/year, making it the largest contributor of electricity. PV module only generated 88,579 kWh/year.

Table 23: Electricity Production Evaluation for Configuration C

Quantity	kWh/year	(%)
Excess Electricity	17,166	7.67
Unmet Electric Load	1.17	0.0006
Capacity Shortage	26.6	0.0133

The total unmet electric load is infinitesimal. Hence, this combination is proven to be feasible. Figure 23 and Figure 24 shows the power output per day for diesel genset and PV module.

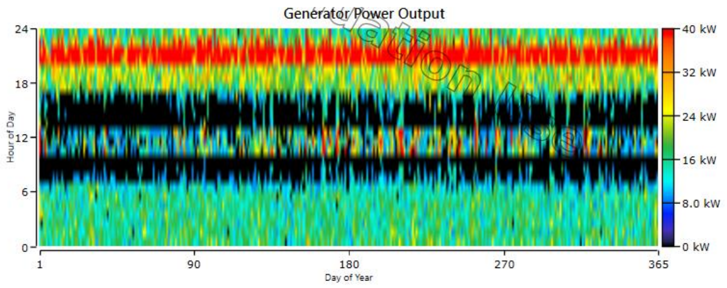

Figure 23: Power output per day for diesel genset in Configuration C

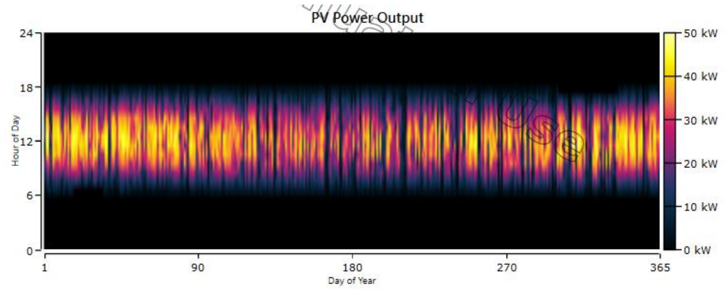

Figure 24: Power Output per day for PV in Configuration C

As shown from Figure 23, diesel generator output most of the power, especially during the peak load at night. The total diesel fuel used per year is 41,462 litres. Below show the emissions produced from this configuration.

Table 24: Emission type and amount by Configuration C

Quantity	Value (kg/year)
Carbon Dioxide	108,447
Carbon Monoxide	738
Unburned Hydrocarbons	29.9
Particulate Matter	2.95
Sulphur Dioxide	266
Nitrogen Oxides	59

Configuration D – Biogas/Diesel/Battery/Converter

Table 25 shows the results for this configuration.

Table 25: Economics of Configuration D

Diesel price ($/litre)	Biogas (kW)	Diesel (kW)	Lead Acid (Qt)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/year)	RF (%)
0.80	20.0	40.0	50	20.0	CC	670,278	0.249	42,607	75.4
0.90	20.0	40.0	50	20.0	CC	690,213	0.256	44,089	75.7
1.00	20.0	40.0	50	20.0	CC	710,121	0.264	45,568	76
1.10	20.0	40.0	50	20.0	CC	729,840	0.271	47,034	76.1
1.20	20.0	40.0	50	20.0	CC	749,561	0.278	48,500	76.1

Table 26: Cost Summary for Configuration D

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Lead Acid	15,000.00	23,504.01	6,727.47	0.00	530.99	44,700.49
Biogas Genset	60,000.00	0.00	233,900.64	106,139.23	51.27	399,988.59
Diesel Genset	16,000.00	23,157.37	22,076.86	158,641.98	2,458.66	217,417.54
Converter	6,000.00	2,699.57	0.00	0.00	528.37	8,171.20
System	97,000.00	49,360.95	262,704.97	264781.21	3,569.29	670,277.82

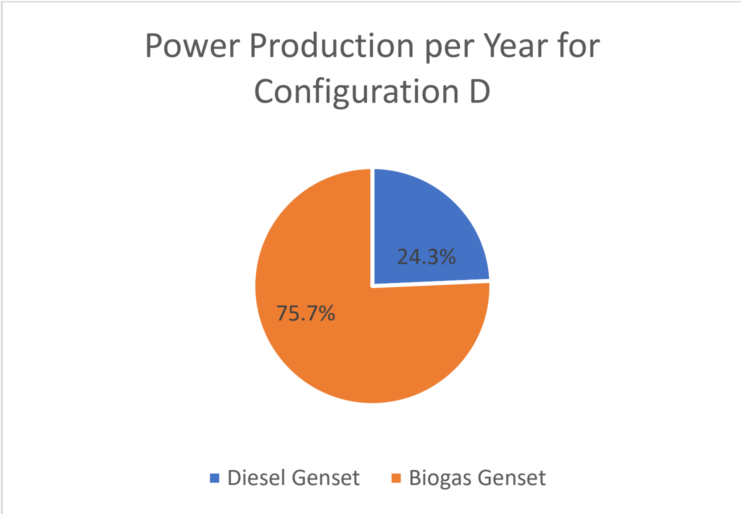

Figure 25: Contribution of Power Output per power module for Configuration D

Biogas genset contributed the most electricity, which is 153,527 kWh/year. Diesel genset only yield 49,174 kWh/year. This shows that Cambodia's livestock and crop wastes might be ample to produce enough energy for consumers and reduce the reliance on diesel combustion, if cost is not a factor on the winning configuration.

Table 27: Electricity Production Evaluation for Configuration D

Quantity	kWh/year	(%)
Excess Electricity	419	0.207
Unmet Electric Load	13.7	0.0068
Capacity Shortage	98.7	0.0493

The total unmet electric load is very small, system is feasible. Figure 26 and Figure 27 shows the power output per day for biogas genset and diesel genset.

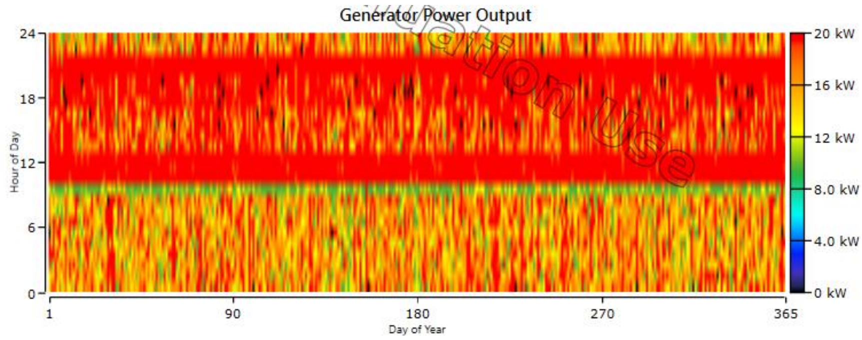

Figure 26: Biogas genset power output per day for Configuration D

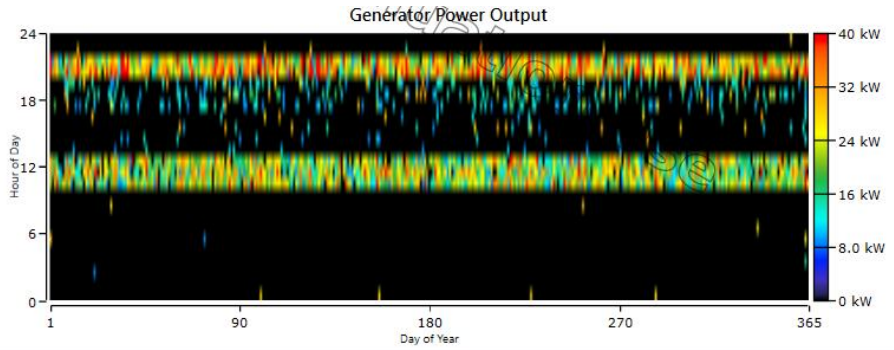

Figure 27: Diesel genset power output per day for Configuration D

From Figure 26 and Figure 27, it is shown that most load is satisfied through biogas generator. Diesel generator only supply power to assist biogas generator in meeting the peak loads. Total diesel fuel used is 14,738 litre/year. Total biomass resources consumed is 463 tonnes/year. Below show the emissions produced by configuration D.

Table 28: Emission type and amount by Configuration D

Quantity	Value (kg/year)
Carbon Dioxide	38,718
Carbon Monoxide	263
Unburned Hydrocarbons	10.6
Particulate Matter	1.05
Sulphur Dioxide	94.5
Nitrogen Oxides	21.6

Conclusion

In this techno-economic study, 4 different configurations of off-grid hybrid renewable energy model are proposed and tested with HOMER software to verify the most economically optimum power supply strategy to satisfy the load demand for 25 households in an unelectrified rural village in Cambodia, known as Prey Preal. From the simulation results, all configurations have a negligible unmet load, rendering all configurations feasible.

Out of the 4 configurations, Configuration A, constituted by a 20 kW PV module, 20 kW biogas generator, 40 kW diesel generator, 50 1kWh lead acid batteries and 20 kW converter has the lowest NPC which is USD $658,476, hence it is the most economical configuration and will be chosen out of the rest. This configuration has a COE of USD $0.244, operation cost of USD $38,014/year and a renewable fraction of 80.3%. Despite being the winning configuration, it emits 31,717 kg of CO_2, 216 kg of CO, 77.4 kg of SO_2 and 17.7 kg of NO_x (oxides of nitrogen) each year. Although this amount is not the highest compare to Configuration C, it can vastly exacerbate the plaguing of Earth by greenhouse effect and acid rain. If cost isn't the concern, a more eco-friendly and viable option is Configuration B. This combination is fully renewable, with a negligible yield of greenhouse gases.

Next, it is shown in Table 15, Table 19, Table 23 and Table 27 that each configuration yield excess electricity. This electricity can be sold to electricity distributor if a grid is connected to the power source in the future or be used to produce biofuels to be stored through Power-to-Gas technologies.

From the HOMER simulations, it is prominent that renewable generation technologies are very expensive. Therefore, related parties be it government or non-government bodies must subsidized the cost of using renewable energy to ensure renewable energy is widely adopted across the globe. Cambodia is a country blessed with abundant biomass resources and good solar irradiance. If RGC continues with their Master Plan, there is a lot of potential and future for renewable energy generation in Cambodia and this report shall be a stepping stone to prove it.

References

1. *Cambodia Rural Electrification Strategy and Implementation Plan-Final Report 2009*. 2009. http://documents.worldbank.org/curated/en/635301468014998063/pdf/701160ESW0P1140gy0Impl0Plan0P114368.pdf
2. National Institute of Statistics, M.o.P., *Cambodia Socio-Economic Survey 2017*. 2018. http://www.nis.gov.kh/nis/CSES/Final%20Report%20CSES%202017.pdf
3. National Institute of Statistics, M.o.P., *Census of Agriculture in Cambodia Preliminary Report 2013*. 2014. http://www.fao.org/3/I9465EN/i9465en.pdf
4. Pode, R., *Potential applications of rice husk ash waste from rice husk biomass power plant*. Renewable and Sustainable Energy Reviews, 2016. **53**: p. 1468-1485. http://www.sciencedirect.com/science/article/pii/S1364032115010217
5. Bhatt, A., M.P. Sharma, and R.P. Saini, *Feasibility and sensitivity analysis of an off-grid micro hydro–photovoltaic–biomass and biogas–diesel–battery hybrid energy system for a remote area in Uttarakhand state, India*. Renewable and Sustainable Energy Reviews, 2016. **61**: p. 53-69. http://www.sciencedirect.com/science/article/pii/S1364032116002653
6. Hossain, M., S. Mekhilef, and L. Olatomiwa, *Performance evaluation of a stand-alone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia*. Sustainable Cities and Society, 2017. **28**: p. 358-366. http://www.sciencedirect.com/science/article/pii/S2210670716302670
7. Das, B.K., et al., *A techno-economic feasibility of a stand-alone hybrid power generation for remote area application in Bangladesh*. Energy, 2017. **134**: p. 775-788. http://www.sciencedirect.com/science/article/pii/S0360544217310162
8. Yilmaz, S. and F. Dincer, *Optimal design of hybrid PV-Diesel-Battery systems for isolated lands: A case study for Kilis, Turkey*. Renewable and Sustainable Energy Reviews, 2017. **77**: p. 344-352. http://www.sciencedirect.com/science/article/pii/S136403211730535X
9. Sawle, Y., S.C. Gupta, and A.K. Bohre, *Socio-techno-economic design of hybrid renewable energy system using optimization techniques*. Renewable Energy, 2018. **119**: p. 459-472. http://www.sciencedirect.com/science/article/pii/S096014811731159X
10. Duman, A.C. and Ö. Güler, *Techno-economic analysis of off-grid PV/wind/fuel cell hybrid system combinations with a comparison of regularly and seasonally occupied households*. Sustainable Cities and Society, 2018. **42**: p. 107-126. http://www.sciencedirect.com/science/article/pii/S2210670718300908
11. Fodhil, F., A. Hamidat, and O. Nadjemi, *Potential, optimization and sensitivity analysis of photovoltaic-diesel-battery hybrid energy system for rural electrification in Algeria*. Energy, 2019. **169**: p. 613-624. http://www.sciencedirect.com/science/article/pii/S0360544218324150
12. Javed, M.S., A. Song, and T. Ma, *Techno-economic assessment of a stand-alone hybrid solar-wind-battery system for a remote island using genetic algorithm*. Energy, 2019. **176**: p. 704-717. http://www.sciencedirect.com/science/article/pii/S036054421930547X
13. J.I.C.A, *Data Collection Survey on electric power sector in cambodia*. 2012. https://data.opendevelopmentmekong.net/library_record/data-collection-survey-on-electric-power-sector-in-cambodia
14. Lab, N.R.E., *National Solar Radiation Database*. 2019. https://nsrdb.nrel.gov/
15. Abdeshahian, P., et al., *Potential of biogas production from farm animal waste in Malaysia*. Renewable and Sustainable Energy Reviews, 2016. **60**: p. 714-723. http://www.sciencedirect.com/science/article/pii/S1364032116001477

16. Akgün, O., et al., *Theoretical Bioenergy Potential in Cambodia and Laos.* 2011. https://www.researchgate.net/publication/266592043_Theoretical_Bioenergy_Potential_in_Cambodia_and_Laos
17. Nguyen, H.N., M. Ha-Duong, and L. Van de Steene, *A critical look at rice husk gasification in Cambodia: Technology and sustainability.* Vietnam Academy of Science and Technology Journal of Science and Technology, 2015: p. 247-252. https://hal.archives-ouvertes.fr/hal-01166547
18. *NASA Surface meteorology and Solar Energy database.* 2019. http://www.eso.org/gen-fac/pubs/astclim/espas/world/Climate/ITCZ/ION/ion-pwv.html