# RURAL ELECTRIFICATION PLANNING FOR PRASAT SAMBOUR DISTRICT, CAMBODIA

**BY**

**CHHUNHENG LAO**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING AND TECHNOLOGY)**
**SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY**
**THAMMASAT UNIVERSITY**
**ACADEMIC YEAR 2017**

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A Thesis Presented

By

CHHUNHENG LAO

Submitted to

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Approved as to style and content by

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# Abstract

RURAL ELECTRIFICATION PLANNING FOR
PRASAT SAMBOR DISTRICT, CAMBODIA

by

CHHUNHENG LAO

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Electricity is a basic need of people around the world. In developing countries, a shortage of rural electrification is the main obstacle for social-economic development. Cambodia is one of the countries in Southeast Asia, which was afflicted by war over several decades. All sectors were damaged by war, especially the electric utility sector. After the war, the electricity sector in the country has been dependent on fossil fuel generation. The Cambodian government has a policy to provide all villages in Cambodia access to electricity of some type by 2020. Moreover, by the year 2030, the government expects that 70% of households will have access to power quality grid connections. However, since 80% of the population live in rural areas, this goal is quite challenging. So far, some large-scale hydro and coal-fired power plants have been built to fulfill the demand. But it will take a few more years for the rural areas, to be directly connected with national quality grid systems. Renewable energy, which is defined as a clean and environmentally-friendly energy, is a good option to cope with this matter. This research presents appropriate options for rural electrification in Cambodia. HOMER is used as a techno-economic analysis software program. Prasat Sambour is the selected district in this study. Six scenarios have been studied which include both off-grid and on-grid options. These comprise diesel-only; PV with battery; diesel/PV with battery; grid only, grid with PV, and grid/PV with battery systems. The study gives an overview of the future energy development plan in the district as well as promoting the utilization of renewable energy. In addition, it also provides the rural community access to better living conditions with affordable and reliable electricity energy supply, thereby supporting the target of the royal government of Cambodia that all villages be electrified by the year 2020.

**Keywords**: Rural electrification, renewable energy, HOMER, hybrid system.

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# Chapter 1
# Introduction

## 1.1 General background

Cambodia is one of the countries in Southeast Asia which suffered from civil war over several decades. All sectors in the country were damaged by war, especially the electricity sector. After the war, the country's economy is better from day to day. The growth of GDP per capita is about 7% annually. Due to this rapid growth, the ADB has promoted Cambodia to be a lower-middle income country in 2016. Nevertheless, Cambodia still needs to import electricity from neighboring countries. This is due to a shortage of electricity supply from hydropower plants and the increase peak demand during the dry season. Consequently, by importing fossil fuel and having insufficient electricity infrastructure, the electric tariff of the country is relatively high compared to other ASEAN countries.

The Royal Government of Cambodia (RGC) plans to provide power to all villages in Cambodia by 2020 and give 70% of the households' access to quality grid electricity by 2030. Moreover, the government also has an action plan to reduce carbon emission by 3 million tons by 2035 (MIME, 2013). So far, the grid extension and generation capacity expansion are underway. Electric tariffs in Cambodia will continue to decline due to additional capacity generation from hydro and coal-fired power plants. However, for rural areas far from grid systems, the tariff is still high compared with urban areas. The price is solely dependent on the fuel generation source. As of August 2016, the tariffs of electricity generated from diesel varied from 1600 riel (0.40 USD) to 2700 riel (0.68 USD) in rural areas. This is due to the high cost of grid transmission lines, and low density of population, as well as voltage drop.

Various options for rural electrification include grid expansion, stand-alone diesel generation, mini-grid, cross-border power supply from neighboring countries and renewable energy. In the short and medium term, a hybrid system comprising renewable resources and conventional diesel generators will play a key role in accelerating the rural electrification rate in the country (ADB, 2015).

## 1.2 Statement of problems

According to the ADB (ADB, 2015), Cambodia has vast renewable energy resources, especially solar and biomass. However, the utilization of renewable energy to generate electricity is still limited. Excluding the hydropower share, other renewable sources are low in the energy generation mix. While 80% of the population is living in rural areas, electrification in remote areas is still a major need for Cambodia's economic development. In remote areas that are far from the national grid, people are still using conventional fuel sources such as kerosene, batteries or diesel to power households. As a result, the tariff in remote areas is higher than that for the cities or towns.

Even though Cambodia's government has tried to diversify its energy generation fuel mix, except for large-scale hydropower, the share of other renewable sources is negligibly small. Biomass, for instance, accounts for only 1% of the total energy generation. According to the first Cambodia's national energy statistics (ERIA, 2016), energy generation has increased about 20% per year from 2,515 GWh in 2010 to 6,186 GWh in 2015. For domestic production, the generation increased about four-fold during 2010-2015, from 968 GWh in 2010 to 4,645 GWh in 2015. On the other hand, the electricity consumption by end users has sharply increased, more than doubling from 2254.04 GWh to 5201.49 GWh in the same period. However, due to the lack of power supply from hydropower in the dry season, Cambodia still must import electricity from neighboring countries to fulfill the peak load demand. Therefore, in order to strengthen the energy security of the country, other renewable energy, solar PV in particular, will play a significant role in coping with the problem.

Prasat Sambour, one of the rural districts in Kampong Thom province of Cambodia, is still disconnected from the national grid system. Only some parts of the district are electrified using diesel generators. Due to carbon dioxide emission from diesel fuel as well as the high electric tariff in the district, alternative energy resources should be considered for power generation.

## 1.3 Objectives of the study

The main objective of this study is to design other alternative power generation systems for rural electrification in Prasat Sambour district, Cambodia. The specific objectives of the study are:

1. To study the potential of solar PV power generation for the rural electrification in Cambodia,
2. To investigate various possible scenarios of hybrid renewable energy generation systems for Prasat Sambour district,
3. To determine the optimal hybrid systems for the district, in techno-economic terms as well as from environmental perspectives, and
4. To investigate the effects of some renewable supporting schemes (Feed-in tariff or net-metering) on the proposed systems.

## 1.4 Scope of the study

The scope of the study has been defined as follows:

- The study focuses only on Prasat Sambour district, Kampong Thom Province.
- Only solar PV is chosen as a renewable energy source for the hybrid systems.
- A well-known software called "HOMER" is used as a tool for simulation and optimization of various hybrid systems in this study.
- Energy demand and load profiles of the district used in this study are based on a recent data collection survey conducted in the district
- Only two renewable supporting schemes: Net-metering and Feed-in tariff are introduced in the study for on-grid option
- As it is a preliminary investigation, system infrastructure planning, stability, and control behavior of the systems are excluded from this study.

## 1.5 Organization of the thesis

The thesis is divided into 8 chapters. The brief details of each chapter are presented as follows:

Chapter 1 "Introduction" offers the general background of the research, statement of problems, objectives of the study, scopes of the study and organization of the thesis.

Chapter 2 "Literature Review" reviews related research work and documents such as current status of power system in Cambodia, targets of rural electrification in Cambodia, status of solar PV in the world and Cambodia, application of hybrid systems in rural electrification, and multi-tier framework for energy access.

Chapter 3 "Methodology" presents the methodology of rural electrification planning, data collection, and scenario development for use in HOMER software.

Chapter 4 "Estimation of Potential Renewable Energy in Kampong Thom" provides the estimated potential of renewable energy in Kampong Thom province and the rationale of district selection.

Chapter 5 "Data preparation for HOMER" provides the information of required data inputs to the HOMER program. These data include technical data, economic data, meteorological data, and load profile as well as equipment characteristics.

Chapter 6 "Results and discussion" provides the simulation results from HOMER, and sensitivity analysis of each scenario as well as discussion of results.

Chapter 7 "Conclusion and recommendation" presents the final conclusions of the thesis work, including recommendations for the rural electrification development plan as well as future research work.

# Chapter 2
# Literature Review

## 2.1 Current status of the power system in Cambodia

Electricity in Cambodia has undergone in recent years. As can be seen from Figure 2.4, in 2010 diesel was the dominant source for power generation, while in 2015 the dominant generation sources were hydro and coal. The national power generation has been increased from year to year. However, electricity still needs to be imported from neighboring countries. This is due to the low capacity power generation of hydro power plants in the dry season and the increase of peak load. Below are the brief details of 2015 (EAC, 2015)&(EAC, 2010):

- Generation installed capacity : 1,657 MW
- Total electricity supplied : 6,186 GWh (Import: 1,541GWh)
- Total electricity consumption : 5,398 GWh
- Imports to domestic generation ratio : 25: 75 (%)
- Village electrification rate : 68.57%

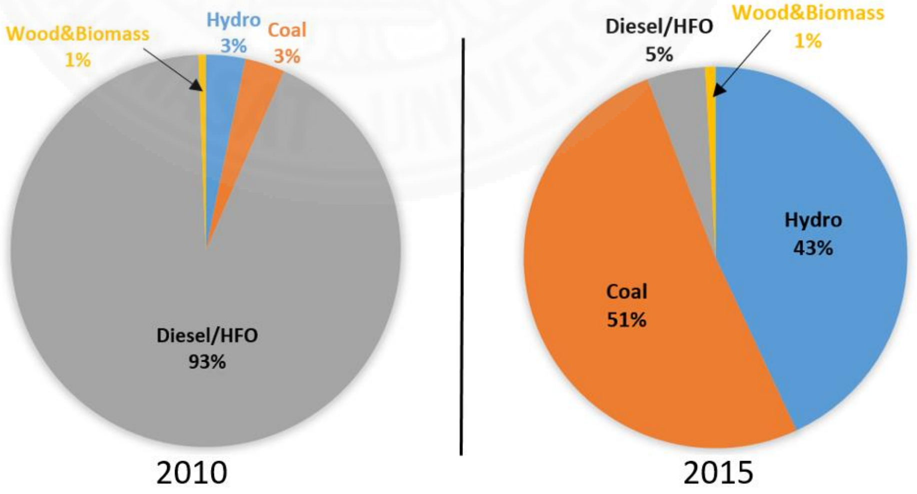


Figure 2.1 Comparison of domestic generation between 2010 and 2015

## 2.2 Targets of rural electrification in Cambodia

According to the report of the Electricity Authority of Cambodia (EAC), only 68.57% of villages in Cambodia are under electrified areas [5]. These electrified areas are mainly in cities and provincial towns. Since more than 80 percent of Cambodian people live in rural areas, providing quality electricity to all households is still a daunting development barrier for the government. To cope with this inequality, the Royal Government of Cambodia has set two major goals for electrification:

1. By the year 2020, all villages in Cambodia will have access to some types of electricity, including access to mini-grid and off-grid electricity.
2. By the year 2030, 70% of households will have access to grid quality electricity.

Furthermore, the implementation of renewable energy in rural electrification is also a goal in the national policy. However, so far there is no set of renewable energy targets as such, either by generation capacity or percentage in generation shares. No renewable energy supporting schemes such as feed-in tariff or net-metering are implemented.

## 2.3 Status of solar PV in the world and Cambodia

Due to current declining costs of solar PV module and battery storage, solar PV systems will be more competitive with conventional fossil fuel generation in the near future. According to IRENA (IRENA, 2016), as of 2015, electricity from solar PV was 13 cents per kWh and will be decreased by 59% in the year 2025. Similarly, the cost of batteries, is estimated to decrease around 47% in the next 5 years. As shown in Figure 2.2, the price of silicon sharply decreased from 76.00$ in 1977 to 0.30$ in 2015.

In Cambodia, implementation of solar energy in power generation is still in the initial stage and mostly consists of small pilot projects. However, due to decreasing solar PV panel costs, RGC is starting to deploy solar PV on a large scale for power generation now. On August 2016, the first large scale 10 MW solar farm project contract was signed between Electricité Du Cambodge (EDC) and Sunseap Asset (Cambodia) Co. Ltd. This project aims to fulfill the demand load of electricity in Svay Rieng province, which mainly relies on imported electricity from Vietnam (EDC, 2016). The tariff is as low as 9.1 cents per kWh since it obtains some financial support from the Asian Development Bank (ADB) and Canadian Climate Fund for the Private Sector in Asia (CFPS). The price of electricity from this solar farm is just about 1 cent higher than the tariff rate of electricity generated from hydropower (de Ferranti, Fulbrook, McGinley, & Higgins, 2016). From ADB's webpage, this solar farm can reduce about 5,500 tons of carbon dioxide equivalent, annually (ADB, 2017).

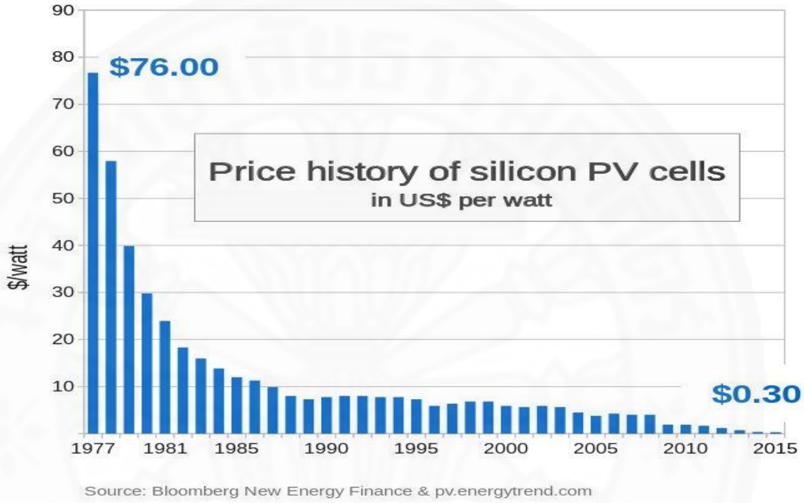


Figure 2.2 Price history of silicon PV cells between 1977 and 2015

## 2.4 Hybrid renewable energy system in rural electrification

In order to gain a general idea of the research, various research works related to application of hybrid renewable energy system in different areas have been reviewed.

Sou, et al. (Sou, Siemers, & Exell, 2010) designed a hybrid system for one rural village in Cambodia. The selected renewable resources are solar and biomass. Daily estimated energy demand was 67.12 kWh, or 24,518 kWh/yr, and the peak load was 15 kW. The hybrid system consisted of 1.27 $kW_P$ solar PV, a 15 $kW_e$ biomass gasification generator, and a 7.28 kWh battery backup. The results showed that 90% of energy demand can be supplied by the biomass gasification system, while 3% can be supplied by solar PV and the remaining 7% by battery. It was found that the system can give the village a self-sufficient energy supply free from imported conventional diesel fuel.

Peerapong and Limmeechokchai (Peerapong & Limmeechokchai, 2017) studied the utilization of the integration of a solar PV system with existing diesel generators in Koh Mak island, Thailand. HOMER was used as the simulation software. Daily consumption load was estimated at 6,693 kWh/day with the peak load of 850 kW. The proposed configurations comprise stand-alone diesel system, and hybrid diesel/PV system with and without battery. Several sensitivity cases such as solar radiation, diesel prices, and real interest rates, as well as demand load variation have been included in the study. It was found that, the optimal scenario was PV system/diesel, which can decrease COE from 0.429$/kWh to 0.374$/kWh when compared to the existing diesel-based system. It can also decrease emissions: carbon dioxide by 796.61 tons/yr and other gases by 21.47 tons/yr. Furthermore, the results found that the system can reduce about 302,510 liters per year of diesel fuel usage and increase the solar PV share to 41% of the total generation.

Arif et al. (Arif, Oo, Ali, & Shafiullah, 2013) investigated the significance of storage on solar PV systems in one suburban area of Australia. HOMER was used as the software in the techno-economic analysis. Both off-grid and on-grid options were analyzed in the study. The findings showed that by utilizing battery storage can reduce cost of electricity (COE), and greenhouse gas (GHG) emissions as well as increase renewable penetration. Comparing solar PV integrated system with and without batteries, it was shown that in a grid connected scenario, GHG can be reduced by 46.47%. Furthermore, the renewable fraction was increased to 93.78% for grid/PV with battery, and that of stand-alone PV system without battery was 40.17%.

Sen and Bhattacharyya (2014) conducted research in one remote village in India. Four different energy resources were selected in the study: hydro, solar, wind, and biodiesel. Different energy consumption sectors have been taken into account to make the energy demand loads more reliable. Both pre- and post- HOMER analysis have been discussed in the study. There is also a comparison between the national grid extension and decentralization of the hybrid system. Results found that, mini-hydro is the best option for the community in terms of electricity generation cost.

Some constraints of renewable resources were found, such as the shortage of water flow in the summer season and the availability of biomass residue.

In summary, rural electrification has gained global attention for both off-grid and on grid scenarios. Because it is both environmentally-friendly and economically feasible for some cases. A simulation program, HOMER, has been used in many hybrid renewable energy system projects around the world. The architecture design of a system must consider different load demands, as well as geographical, meteorological, and local conditions.

## 2.5 Multi-Tier Framework for Measuring Energy Access

The World Bank's Energy Sector Management Assistance Program (ESMAP) has developed a new framework for measuring household energy access. Their newly developed measurement approach is referred to as the multi-tier framework (Bhatia & Angelou, 2015). There are six tiers in this framework which range from zero to five. The detail of each criteria is given in the Figure 2.3. For this study, this framework is used as a baseline reference for forming the energy access compared with the data from the site survey. Details of the questionnaire and methodology will be discussed in the next chapter.

| ATTRIBUTES | | TIER 0 | TIER 1 | TIER 2 | TIER 3 | TIER 4 | TIER 5 |
|---|---|---|---|---|---|---|---|
| 1. Peak Capacity | Power capacity ratings[28] (in W or daily Wh) | | Min 3 W | Min 50 W | Min 200 W | Min 800 W | Min 2 kW |
| | | | Min 12 Wh | Min 200 Wh | Min 1.0 kWh | Min 3.4 kWh | Min 8.2 kWh |
| | OR Services | | Lighting of 1,000 lmhr/day | Electrical lighting, air circulation, television, and phone charging are possible | | | |
| 2. Availability (Duration) | Hours per day | | Min 4 hrs | Min 4 hrs | Min 8 hrs | Min 16 hrs | Min 23 hrs |
| | Hours per evening | | Min 1 hr | Min 2 hrs | Min 3 hrs | Min 4 hrs | Min 4 hrs |
| 3. Reliability | | | | | | Max 14 disruptions per week | Max 3 disruptions per week of total duration <2 hrs |
| 4. Quality | | | | | | Voltage problems do not affect the use of desired appliances | |
| 5. Afford-ability | | | | | Cost of a standard consumption package of 365 kWh/year < 5% of household income | | |
| 6. Legality | | | | | | Bill is paid to the utility, pre-paid card seller, or authorized representative | |
| 7. Health & Safety | | | | | | Absence of past accidents and perception of high risk in the future | |

Figure 2.3 Multi-tier framework of energy access

# Chapter 3
# Methodology

From the literature review in Chapter 2, the research problem and gap of the study are defined. In this chapter, the methodology of rural electrification planning for Prasat Sambour district is presented. To analyze the alternative power supply for electricity generation, various scenarios are constructed. Both on desk research as well as site survey are required for the inputs of HOMER software program. Below is the flow diagram of the methodology.

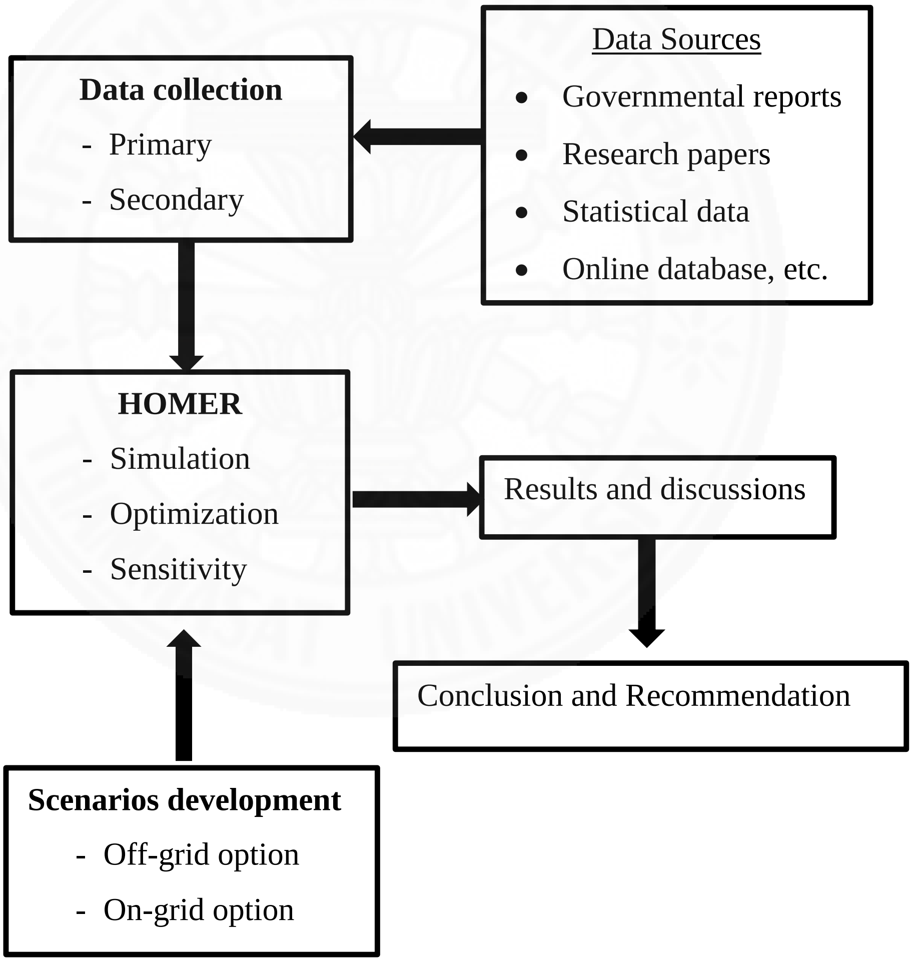


Figure 3.1 Flow diagram of the methodology

The following sub-section will demonstrate the major steps of the methodology such as scenarios development, data collection, and HOMER software which are the key players in the flow diagram.

## 3.1 Scenarios development

For the purpose of electrification planning for the district. both off-grid and on-grid options are investigated in this study. In total, six scenarios are taken into account for the purpose of power generation. These scenarios are as follows:

### 3.1.1 Off-grid options

a. Diesel-only scenario:

The diesel-only scenario is the base case scenario for the off-grid option. In this scenario, it is assumed that, only diesel generators are used for power generation. The system configuration in this scenario has only diesel generators.

b. Diesel/PV scenario:

Diesel/PV is the scenario in which the power demand of the district is covered by the hybrid renewable solar PV with conventional diesel generators. The system configuration in this scenario includes solar PV panel, converter, and diesel generator.

c. Diesel/PV with battery scenario:

In the diesel/PV with battery scenario is the scenario, the district load is supplied by a hybrid renewable solar PV energy with battery storage and diesel generator. The system configuration in this scenario comprises solar PV panel, converter, battery, and diesel generator.

### 3.1.2 On-grid options

c. Grid-only scenario:

The grid-only scenario is the base case scenario for the on-grid option. In this scenario, it is assumed that, only the national grid is used for supplying electricity to the whole district. This scenario comprises only the grid system for power generation.

d. Grid/PV scenario:

In the grid/PV scenario, the power demand of the district is covered by a hybrid renewable solar PV with the national grid system. The system configuration in this scenario includes solar PV panel, converter, and grid system.

e. Grid/PV with battery scenario:

The diesel/PV with battery scenario is the integration of a hybrid renewable solar PV and battery storage with the national grid system. The system configuration includes solar PV panel, converter, battery, and grid system. Figure 3.2 presents the system configuration of each scenario; each component is represented in one box.

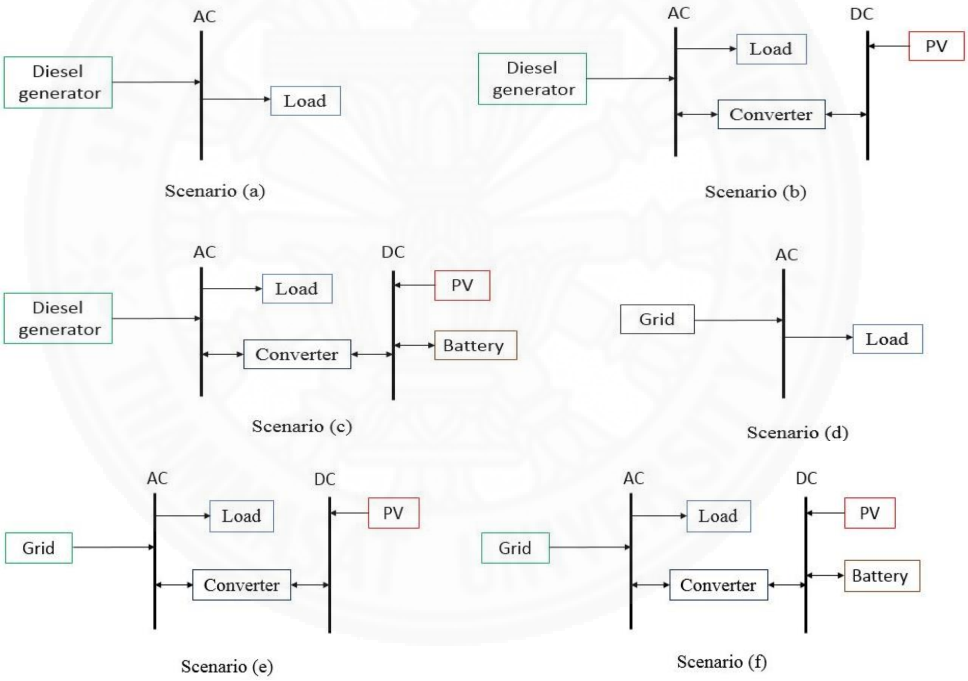


Figure 3.2 System configuration of each scenario

## 3.2 Data collection

Data sources of this study are mainly from official governmental reports, research papers, statistical data, online database, etc. In this study, data collection can be divided into two parts: primary data collection and secondary data collection.

### 3.2.1 Primary data collection

For primary data collection, the quantitative approach is used for the survey of residential electricity load consumption in Prasat Sambour district. The samples are randomly taken from the population by using the formula from (Yamane, 1967) as shown in Equation (3.1).

$$n = \frac{N}{1 + Ne^2} \quad (3.1)$$

Where n is the sample size, N is the number of households in selected district, e is the error level.

In this study: N= 10,453, e=10%=0.1

Then, $n = \frac{10,453}{1+10,453(0.1)^2} = 99.05 \approx 100$

Therefore, total sample size is 100 households. For more detail of the primary data collection and questionnaire, please see Appendix A and B.

### 3.2.2 Secondary data collection

#### 3.2.2.1 Geographical data collection

Geographical data is obtained from governmental documents, site survey and interviews as well as the webpage of Open Development Cambodia (DOC). The development of the maps is done personally on the platform of geographical information system (GIS). The procedure of the map development is shown in Figure 3.3. In total, eight maps have been developed for Prasat Sambour district, which include village map, school map, health center map, river map, community forest map, land concession and protection areas map, main road map, and soil fertility map. These maps are used for the planning process. For more detail of the developed maps, please see Appendix C.

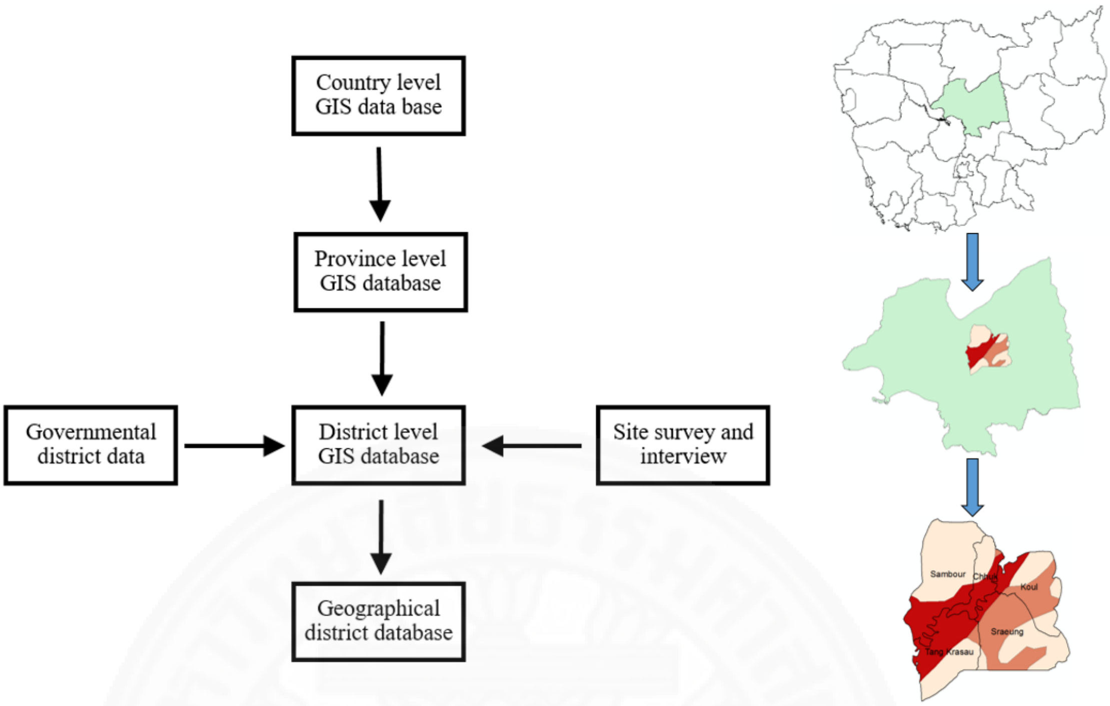


Figure 3.3 Procedure of obtaining geographical data

#### 3.2.2.2 Data inputs of HOMER

For secondary data collection, official governmental reports, research papers, and statistical data as well as online data bases are used in this study.

Figure 3.4 presents the summary block diagram of data inputs and outputs in HOMER.

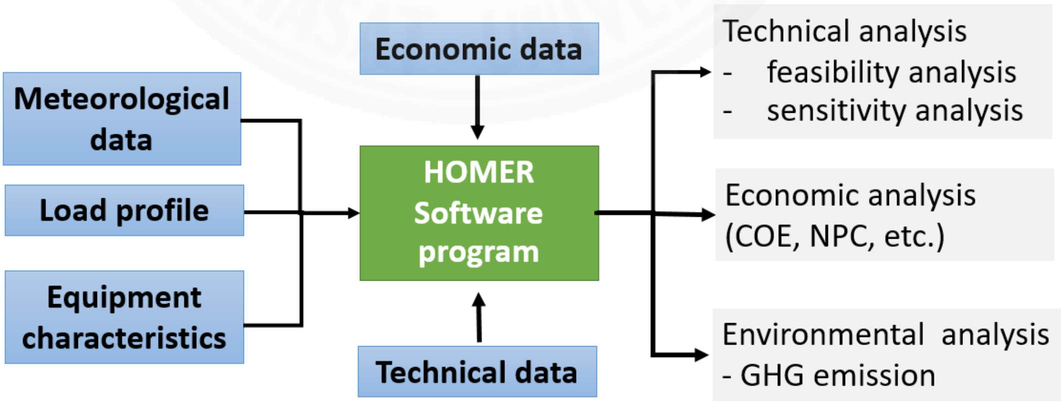


Figure 3.4 Block diagram of data inputs to HOMER

- Meteorological data: data of solar resources are retrieved from NASA surface meteorology and Solar Energy's website (National Aeronautics and Space Administration (NASA)), while temperature data are obtained from local meteorological department.

- Load profiles: data is obtained from the combination of site survey with questionnaire interview and then compared with the World Bank's multi-tier framework of energy access as mentioned in previous chapter.

- Technical and economic data: size and price are obtained from literature review and local suppliers.

- Equipment characteristics: are obtained from literature reviews, local market, and online database.

### 3.3 HOMER model

In this study, the developed scenarios are analyzed by using the Hybrid Optimization of Multiple Energy Resources (HOMER) software. This software was developed by the American National Renewable Energy Laboratory (NREL) which aims to help modelers in energy planning. Three main tasks can be performed in the program:

Simulation: HOMER determines technical feasibility and life cycle costs of a micro grid system. It balances the supply and demand of a micro-grid system for each hour of the year and optimizes the least cost of electricity generation.

Optimization: HOMER generates many different system configurations to determine the best one among available options. It will show available solutions by the sort of net present cost (NPC).

Sensitivity: This analysis will help the designer understand the effects of uncertain variables such as fuel price, load consumption, components cost, and so on.

### 3.3.1 Procedure for rural electrification planning by using HOMER

The procedure for the planning is shown in Figure 3.5. The process includes the review of the electricity sector in Cambodia, the potential of renewable energy resources, data collection, hybrid system modeling, results of analysis, and conclusion. In HOMER, the optimal process can help the system designer figure out the optimal system from many possible solutions. The results of each scenario are sorted according to NPC. The optimal scenario is the system with the lowest NPC. The result of each scenario is ranked from the lowest to the highest NPC.

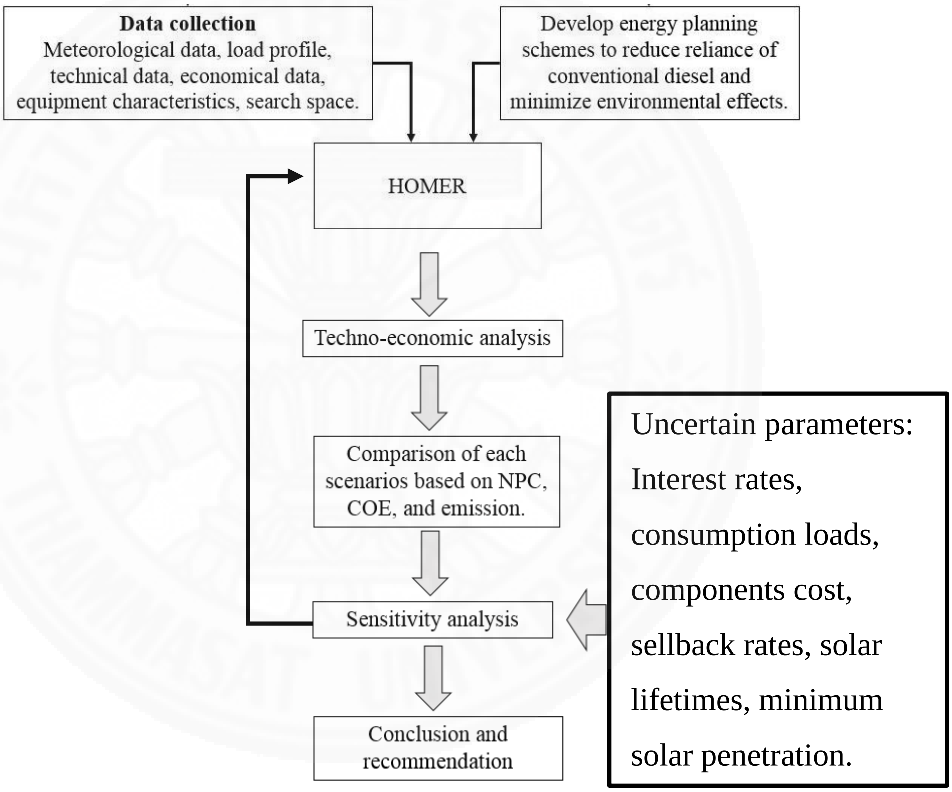


Figure 3.5 Procedure for rural electrification planning by using HOMER

### 3.3.2 Economic and environmental formulas

#### 3.3.2.1 Levelized cost of electricity (COE)

HOMER defines the COE as the average cost per kWh of useful electrical energy produced by the system. To calculate the COE, HOMER divides the annualized cost of producing electricity by the total useful electric energy production.

No thermal or deferrable loads are considered in this study. The equation for the COE is as follows:

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{grid,sale}} \quad (3.2)$$

Where, $C_{ann,tot}$ is total annualized cost ($/yr), $E_{prim}$ and $E_{grid,sale}$ are total electrical energy served to primary load (kWh/yr) and total energy sales back to the grid system (kWh/yr), respectively.

**3.3.2.2 Net Present Cost (NPC)**

NPC is equal to the present value of all costs minus the present value of all revenue over its lifetime. NPC is calculated using Equation (3.3):

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (3.3)$$

where, CRF is the capital recovery factor, i is the interest rate (%), and $R_{proj}$ is the project lifetime (yr). The CRF can be calculated by Equation (3.4):

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3.4)$$

The annual interest rate or real interest rate is the discount rate used to convert between one-time costs and annualized costs. The annual real interest rate is related to the nominal interest rate and can be calculated with Equation (3.5):

$$\text{and } i = \frac{i' - f}{1 + f} \quad (3.5)$$

Where, $i'$ is the nominal interest rate (the loan that we get from a bank) and $f$ is annual inflation rate. According to Cambodia's national bank report (National Bank of Cambodia (NBC), 2016), the average nominal interest rate in 2015 was 12.3%, while the inflation rate from World Bank was 1.2% (World bank).

Then, $i = \frac{0.123 - 0.012}{1 + 0.012}$ = 0.1097 or 10.97% (around 11%)

#### 3.3.2.3 Renewable fraction (RF)

RF is the total annual renewable energy production divided by the total energy production. A higher RE yields a higher renewable energy share in electricity generation. RE can be calculated by Equation (3.6).

$$RF = \frac{E_{RE}}{E_{tot}} \tag{3.6}$$

Where, $E_{RE}$ is the total renewable energy (kWh) and $E_{tot}$ is the total energy generation (kWh).

### 3.3.3 Operating strategies

Dispatch strategy is a set of rules which controls how a system charges its battery bank. If a battery bank and generator are capable to supply net loads and operating reserve; the model will decide how to dispatch them based on their fixed and marginal cost of energy [33]. Two main operating strategies are deployed in HOMER, namely load-following and cycle-charging.

- Load following: generators just generate enough power to serve the required loads, while battery charging and deferrable loads are charged by renewable resources if there is a surplus from renewable resources.

- Cycle charging: whenever a generator operates, it runs at its maximum rated capacity (or as close as possible without incurring excess electricity) and charge the battery bank with the excess. This strategy will help generators operates with good efficiency.

# Chapter 4
# Estimation of Renewable Energy in Kampong Thom

Cambodia has abundant renewable resources throughout the country, most of which are still unutilized. According to the report of the ADB, solar and biomass are the most promising renewable resources for the country (ADB, 2015). Kampong Thom is one of the provinces in Cambodia which is still decentralized from the national grid system. This chapter investigates the potential energy in the province and rationale for the district selection.

## 4.1 Calculation approach

The available potential of renewable energy in Kampong Thom, in terms of solar, agricultural biomass, and biogas from livestock can be calculated as follows:

<u>Estimate of Area of Solar PV's panels</u>

Required area of PV modules can be estimated by considering the panel generation factor, energy required from PV, and watt peak of PV cells (Khatri, 2016). The calculation is done by using Equations (4.1) -(4.4):

$$\text{Panel generation factor } = \frac{\text{Daily solar radiation}}{\text{Standard test irradiance of PV pannels}} \tag{4.1}$$

$$E_{\text{Required}} = E_{\text{demand}} * \text{system loss compensation factor} \tag{4.2}$$

$$W_{\text{peak}} = \frac{E_{\text{Required}}}{\text{Annual Panel generation factor}} \tag{4.3}$$

$$\text{Required area} = \frac{W_{\text{peak}}}{\text{Standard irradiance} * \text{ solar efficency}} \tag{4.4}$$

where $E_{\text{Required}}$ is energy required from PV modules (MWh), $E_{\text{demand}}$ is energy demand in Kampong Thom (MWh), and $W_{\text{peak}}$ is watt peak rating of solar panels ($MW_{\text{Peak}}$). In this study, system loss compensation factor and solar panel efficiency are assumed to be 1.30 and 15%, respectively. It is noticed that, the required area is referred to the total area of solar PV panels. If we consider the working space, the gap between panels, more areas are required.

Agricultural biomass

The energy potential of biomass in the form of agricultural residues can be estimated by using the data of the annual crop harvested from the Ministry of Agriculture, Forestry and Fisheries (MAFF, 2016). The potential energy of each residue is estimated by using the following equations (Bhattacharya et al., 2005) as shown in Equation (4.5)-(4.6):

$$\mathrm{ARG} = \mathrm{ACP} \times \mathrm{RPR} \quad (4.5)$$

$$\mathrm{TEP} = \mathrm{ARG} \times (\mathrm{SAF} + \mathrm{EUF}) \times \mathrm{LHV_{residue}} \quad (4.6)$$

where ARG is annual amount of residue generated (kg/yr), ACP is annual crop production (kg/yr), RPR is residue to product ratio, TEP is total energy potential of agricultural residues (MJ/yr), SAF is surplus availability factor, EUF is energy use factor, and $LHV_{residue}$ is low heating value of residue (MJ/kg).

Biogas

In order to calculate the potential of biogas generation from animal wastes, initial data was collected from the Ministry of Agriculture, Forestry and Fisheries(MAFF, 2016). Annual theoretical energy of biogas from each type of livestock (ADB, 2015; Bhattacharya et al., 2005) can be estimated as Eq (4.7):

$$\mathrm{EP_{manure}} = \mathrm{N_{animal}} * \mathrm{DP} * \%\mathrm{DM} * \mathrm{Y_{biogas}} * \mathrm{LHV_{biogas}} * 365 \quad (4.7)$$

where $EP_{manure}$ is energy potential from livestock manure, $N_{animal}$ is number of animals, DP is daily matter production (kg/animal/day), %DM is dry matter factor, $Y_{biogas}$ is the mean of biogas yield ($m^3$/kg.DM), and $LHV_{biogas}$ is low heating value of biogas (MJ/$m^3$). In this study, a low heating value of biogas of 20MJ/$m^3$ is used (Kayasith Sadettanh, 2004).

## 4.2 Results of the estimation

According to the calculation, the renewable energy in Kampong Thom in solar, agricultural biomass, and animal wastes can be represented as follows:

### 4.2.1 Potential of solar PV

As shown in Table 4.1, if all demand electricity energy in Kampong Thom in 2030 is to be covered by PV systems, only 28.09 ha of area is needed to install solar PV panels. Therefore, there is a good potential for solar PV energy in the province.

Table 4.1 Potential of solar PV to supply load demand in 2030

| Demand Energy in 2030 (GWh) | Required Energy from PV (GWh) | Watt Peak ($MW_{Peak}$) | Required Area for solar panels (ha) | Required area for solar farm (ha) |
|---|---|---|---|---|
| 62 | 80.6 | 42.14 | 28.09 | 44.94 |

### 4.2.2 Potential of Biomass energy

As shown in Table 4.2, about 4,395 TJ of energy can be harnessed from residues of agricultural crops. Residue from paddy rice, rice husk in particular, has the most potential, as it can generate up to 57% of entire heat energy generation. Approximately, 2kg of rice husk is required for generating 1 kWh of electricity energy (Nippon Koei Co. Ltd, 2005). Therefore, total estimated electricity from rice husk is around 98 GWh per year, more than five-fold of energy demand in 2015. In addition, due to the demand growth of the global cashew nut market, the plantation of cashew trees in the province is increasing annually. Cashew nut shells have a high heating value and are a good fuel source for direct combustion for power generation (Abe et al., 2007). However, so far there is no available data in total cashew nut production since most raw cashew nuts are sold to middle men for further informal trade to neighboring countries. For more accurate assessment, further research is needed to determine the amount of cashew nut residues.

Table 4.2 Biomass energy potential from agricultural residues

| Crop type | ACP[a] (tons/yr) | Crop Residue | RPR[b] | ARG (tons) | SAF[b] | EUF[b] | LHV[b] (MJ/kg) | TEP ( TJ/yr) |
|---|---|---|---|---|---|---|---|---|
| Rice | 723,228 | husk | 0.27 | 195,271.56 | 0.469 | 0.531 | 12.85 | 2,509.24 |
| | | straw | 0.33 | 238,665.24 | 0.684 | 0 | 8.83 | 1,441.47 |
| Cassava | 703,646 | stalk | 0.088 | 61,920.85 | 0.407 | 0 | 16.99 | 428.18 |
| Corn | 3,425 | cob | 0.25 | 856.25 | 0.67 | 0.193 | 16.63 | 12.29 |
| Sugar-Cane | 1,045 | top&trash | 0.302 | 315.59 | 0.986 | 0 | 6.82 | 2.12 |
| | | bagasse | 0.25 | 261.25 | 0.207 | 0.793 | 6.43 | 1.68 |
| | | | | | | | TOTAL | 4,394.98 |

### 4.2.3 Potential of Biogas from livestock manure

From Table 4.3, the estimated energy potential from livestock wastes is around 1,240 TJ/yr or a daily biogas potential of 169,829 $m^3$/day. Pigs have the greatest potential, up to 98,455 $m^3$ of biogas per day. It is noticed that, this is just a preliminary estimate of energy from livestock wastes. Since all livestock range-feed throughout the province, collecting all livestock wastes is a challenging issue. Nevertheless, there are seven pig farms in Kampong Thom, which contains 13,344 pigs. This number of pigs has the potential in biogas generation on a commercial scale and will contribute significantly to provincial electricity development.

Table 4.3 Potential of biogas from live stock in Kampong Thom

| Livestock | $N_{animal}^{a}$ | $DP^{b,c}$ ( kg/head/day ) | %$DM^{c}$ | $Y_{biogas}^{b,\,c}$ | DBP ($m^3$/day) | $EP_{biogas}$ (TJ/yr) |
|---|---|---|---|---|---|---|
| Buffalo | 34,315 | 8.00 | 16 | 0.250 | 10,980.80 | 80.16 |
| Cattle | 165,349 | 8.00 | 16 | 0.250 | 52,911.68 | 386.26 |
| Pig | 68,946 | 2.00 | 17 | 4.2 | 98,454.89 | 718.72 |
| Chicken | 650,589 | 0.08 | 25 | 0.575 | 7,481.77 | 54.62 |
| | | | | TOTAL | 169,829.14 | 1,239.75 |

Sources: a. (MAFF, 2016), b. (ADB, 2015), c. (Bond & Templeton, 2011)

## 4.3 Rationale of district selection

There are eight districts in Kampong Thom province. However, Prasat Sambour district is chosen to study due to the following reasons:

1. The electricity in the district is mainly supplied by diesel fuel. This kind of power generation is expensive and harmful to the environment. Alternative power generation methods need to consider.
2. Prasat Sambour has the UNESCO cultural heritage site: “Sambor Prei kuk”. The potential development of the district is high. Therefore, energy planning for the district needs consideration.
3. High potential of solar PV for power generation and the declination in cost of solar PV components.

The next chapter will provide details of Prasat Sambour district as well as data preparation for analysis in HOMER.

# Chapter 5
# Data preparation for HOMER

## 5.1 Prasat Sambour district profile

Prasat Sambour is one of the districts in Kampong Thom. The district has latitude of 12.8870 N and longitude of 105.0690 E. It is located about 170 km from Phnom Penh city and 30 km from the provincial town of Kampong Thom. There are many ancient temples in the district. The famous archeological site in the district, Sambor Prei kuk, was registered as UNESCO world heritage site on July, 2017. Therefore, the prospect for future development in the district is relatively high.

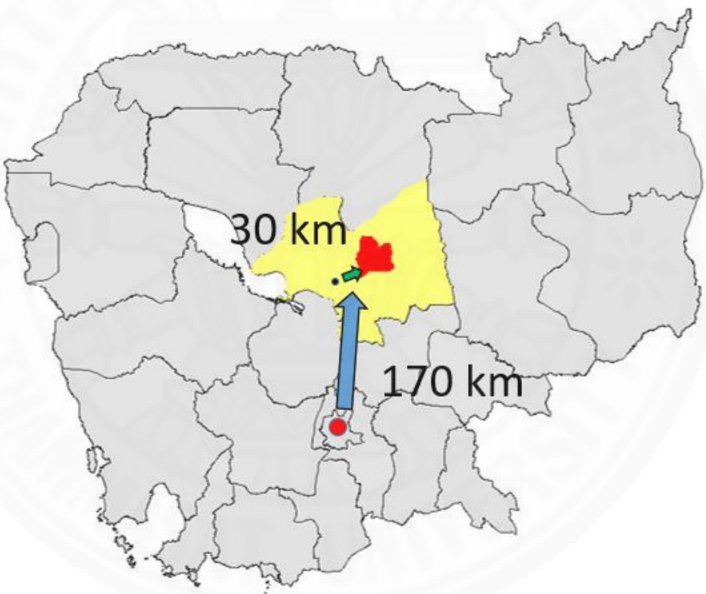


Figure 5.1 Map of Prasat Sambour district

As shown in Table 5.1, there are 10,453 households in the five communes. On average, poverty rate in district is 24.43%, which is 5.67% higher than other parts of the country (MOP, 2015). Sambour is the largest commune in terms of population with 46,011 people. The administration of the district is located in Prasat Sambour commune. In the district, the majority of the residents are farmers.

Table 5.1 Details of each commune in Prasat Sambour

| Commune | Number of villages | Number of households | Number of population | Poverty rate |
|---|---|---|---|---|
| Chhuk | 16 | 2,511 | 10,891 | 23.81% |
| Koul | 11 | 1,230 | 5,016 | 25.41% |
| Sambour | 15 | 2,984 | 13,648 | 24.64% |
| Sraeung | 9 | 1,267 | 5,605 | 26.87% |
| Tang Kra Sau | 15 | 2,461 | 10,851 | 22.72% |
| **TOTAL** | 66 | 10,453 | 46,011 | **Avg**: 24.43% |

## 5.2 Load demand

A survey of electrical consumption in households has been conducted for the purpose of understanding recent and future demand of electrical load in Prasat Sambour district. One hundred households were randomly selected from the five communes. As shown in Figure 5.2, electricity generation is mainly supplied by an electric licensee. Solar energy is widely used for the remote households where the electrical grid is inaccessible. For battery and kerosene, usage proportion is low and commonly used by poor households.

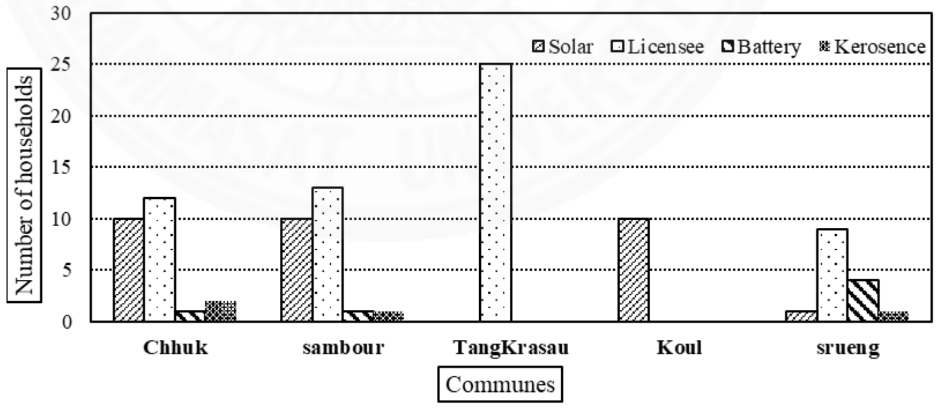


Figure 5.2 Energy generation source from selected households

From Figure 5.3, current electrical consumption of the households is still low. The main usage occurs in early morning, at lunchtime, and in the evening. Because a majority of people spend most of their time outside, for instance, in the rice fields. At noon time, most of the family members come back home for lunch and other activities. From the survey, the daily electric consumption is around 0.8 kWh/day. The main electric appliances in the house are lamps, television and electric fans.

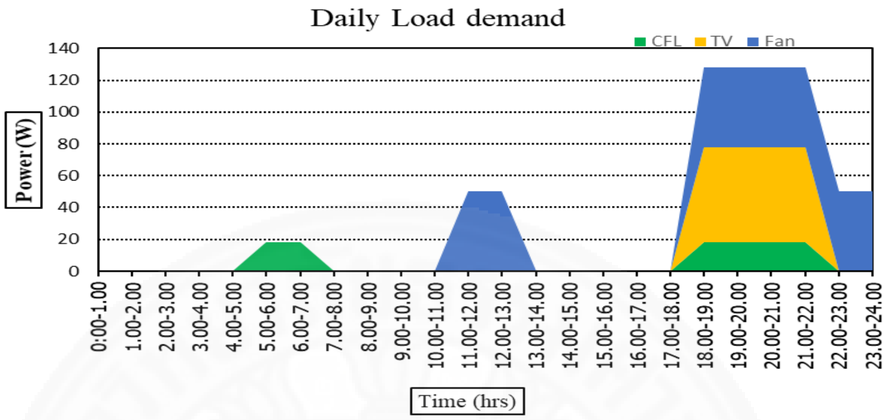


Figure 5.3 Average daily load profile of survey households

Comparing the result with World Bank's multi-tier energy access framework, the level of energy access of residents in Prasat Sambour is in tier II. It is assumed that, when all households are electrified, the consumption level will increase to tier III. This assumption is made regarding the discussion with local households and lesson learned from other rural areas in Cambodia. In this study, residential houses, 3 health centers and 44 schools in the district are considered as the primary demand load. The data of health centers and schools are retrieved from database. However, the dominant load in electric consumption is the residential sector. More details of the loads can see in Appendix D.

## 5.3 Meteorological data

### 5.3.1 Solar resource

The data of global solar radiation in the district are obtained from NASA webpage (National Aeronautics and Space Administration (NASA)). As shown in Figure 5.2, solar radiation is relatively high in the dry season and low in the rainy season. Daily solar irradiance and clearness index are 5.295 kWh/m$^2$/day and 0.543, respectively.

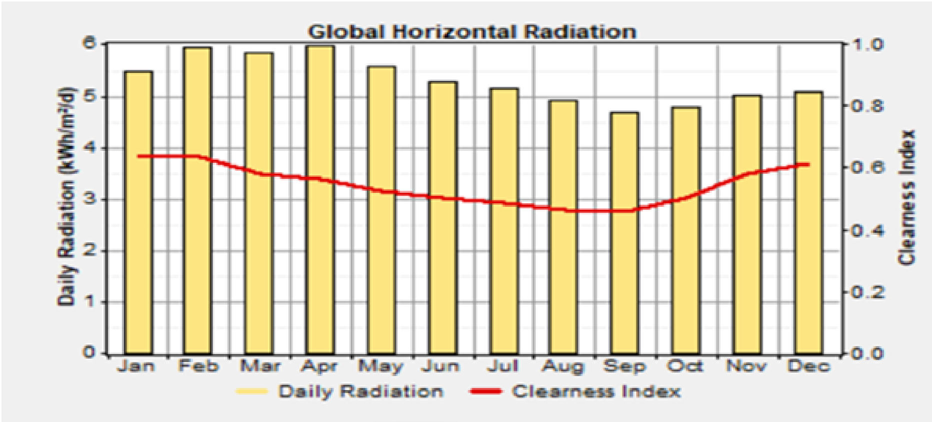


Figure 5.4 Solar radiation in Prasat Sambour district

### 5.3.2 Temperature

Temperature data are taken from the meteorological department. As shown in Figure 5.5, the temperature in the district is relatively high in dry season and low in rainy season. This is due to the climate situation in the district which is affected by monsoon weather.

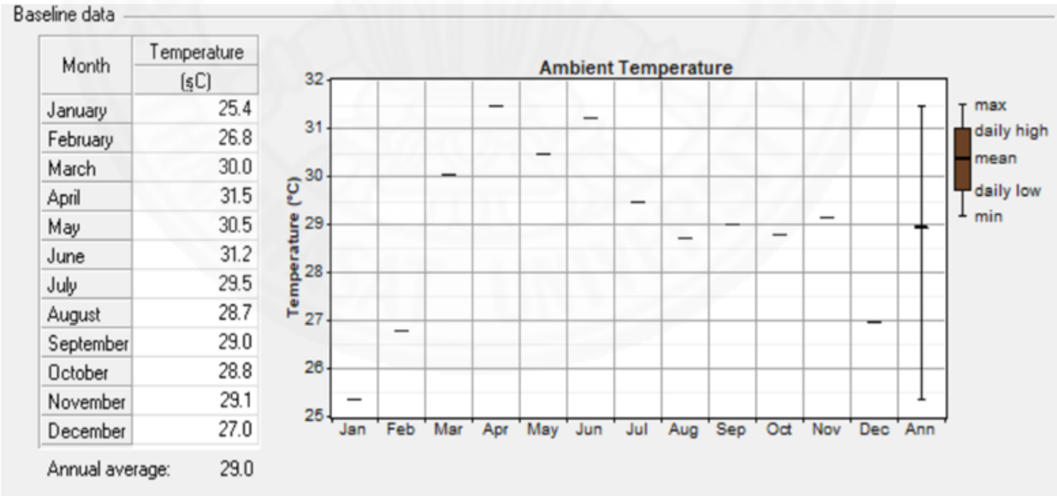


Figure 5.5 Average ambient temperature in Kampong Thom province

## 5.4 Technical and economic data

### 5.4.1 Solar PV

The report of IRENA (IRENA, 2016), as of 2015, shows the average country level of solar PV module prices ranged from 0.52$ to 0.72$/W, while solar PV system investment cost was 1,810$/kW. In Cambodia, the price of solar panels is varied from 1200$ to 3200$ per kW, due to diversity of brands and manufacturing. In this study, 1500$/kW of solar PV capital cost was chosen. The replacement cost is assumed to be the same as capital cost, while operating and maintenance cost (O&M) is assumed to be 10$/yr (Lau, Muhamad, Arief, Tan, & Yatim, 2016). Table 5.2 shows the specification for the selected solar PV model.

Table 5.2 Specification of solar panel

| **PV model** | **STP280-24/Vd** |
|---|---|
| Maximum power at STC ($P_{max}$) | 280 $W_P$ |
| Type of cell | Polycrystalline silicon |
| Cell configuration | 72 (6 × 12) |
| Open circuit voltage ($V_{OC}$) | 44.8 V |
| Short circuit current ($I_{SC}$) | 8.33 A |
| Maximum power voltage ($V_{pm}$) | 32.0 V |
| Maximum power current ($I_{pm}$) | 6.39 A |
| Module efficiency | 14.4% |
| Nominal Operating Cell Temperature (NOCT) | 45 ± 2°C |
| Temperature coefficient of $P_{max}$ | -0.47 %/°C |
| Dimensions | 1956 × 992 × 50 mm |
| Weight | 27 kg |
| Operating temperature | -40 °C to +85 °C |

### 5.4.2 Battery

Due to the intermittent, seasonal variation, and geographical dependence of solar energy, a battery is normally chosen as back up storage to supply the load. In this study, the Surret 6CS25P, whose characteristics are provided in HOMER library, was used in simulation.

### 5.4.3 Converter

A converter is a component used for changing electric current from Direct Current (DC) to Alternating Current (AC) in the process called inversion. And from AC to DC in the process called rectification.

### 5.4.4 Generator

As of 2016, only some parts of the district have been electrifed. From the webpage of EAC, the total capacity of generators of rural electricity enterprise is only

99.5 kVA. Therefore, in order to cover the whole district load, installation of three new high capacity generators is proposed in the scenarios that consist of generators. The existing generators will be sold or used as standby instead. More details of technical and economic data can see in Appendix E.

### 5.4.5 Grid system

For the grid system, it is hoped that the national grid will extend to the district in the near future. Cambodia's energy generation share has changed considerably in the recent years. The dominant domestic generation sources are from hydro and coal, while the previous were diesel and heavy fuel oil (HFO). Due to unavailable national grid emission data for recent years. It is necessary to estimate a national grid emission factor. Table 5.3 represents the estimation of total carbon dioxide from each type of generation source in 2015. Data of A and C are obtained from (Paustian, Ravindranath, & van Amstel, 2006), while data B is obtained from (ERIA, 2016).

Table 5.3 The estimation of total carbon dioxide emission in national grid in 2015

| Fuel Type | $CO_2$ emission factor (t-$CO_2$/GJ) **A** | Fuel consumption (kt) **B** | Net calorific value (GJ/t) **C** | Total $CO_2$ emission (kt) **D=A*B*C** |
|---|---|---|---|---|
| Coal | 0.0909 | 1,002.82 | 5.5 | 501.36 |
| Diesel | 0.0726 | 1.46 | 41.4 | 4.39 |
| HFO | 0.0755 | 43.03 | 39.8 | 129.30 |
| Wood and biomass | 0.0950 | 48.56 | 7.9 | 36.45 |
| Hydro | - | - | - | - |
| | | | **TOTAL** | **671.49** |

Total domestic energy generation = Total supplying energy – Total import energy

= 6,186-1,541 = 4,645 GWh

Carbon emission factor from national grid = $\frac{\text{Total carbon dioxide emssion}}{\text{Total domestic generation}}$

= $\frac{671.49}{4,645}$ = 0.1446 kt/GWh

= **<u>0.1446 t/MWh</u>.**

# Chapter 6

# Results and discussion

## 6.1 Electrical load in Prasat Sambour district

As shown in Figure 6.1, the load consumption of Prasat Sambour district is relatively low in daytime. This is because of the majority of the people are farmers and spend most of the time outside their homes, for instance, at rice fileds. At noon time, most of the family members come back from work to have lunch and do other activities. The load consumption sharply increases in the evening because most of the residents are at home enjoying time together.

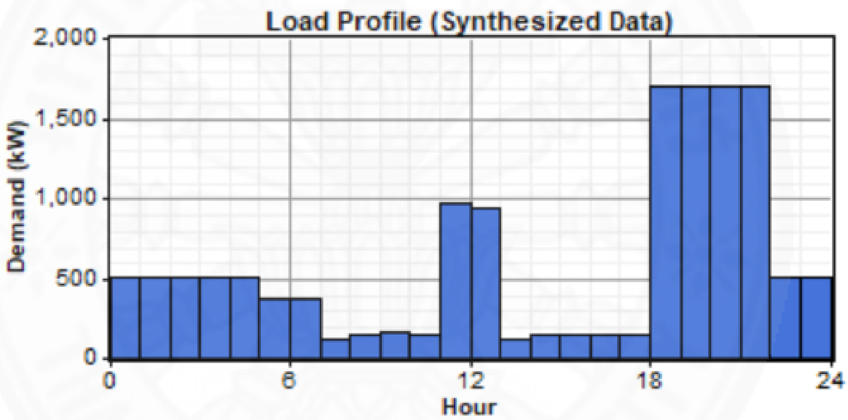


Figure 6.1 Load profile of Prasat Sambour district

As we can see from Figure 6.2, the load consumption varies from month to month. The pattern of load profile is correlated with temperature and seasonal behavior. The consumption is high in the dry season and low in the rainy season. From December to February, the electric consumption is low due to the cold climate conditions in the district. On average, daily electrical consumption and peak load demand are 14.364 MWh/day and 2.3 MW, respectively.

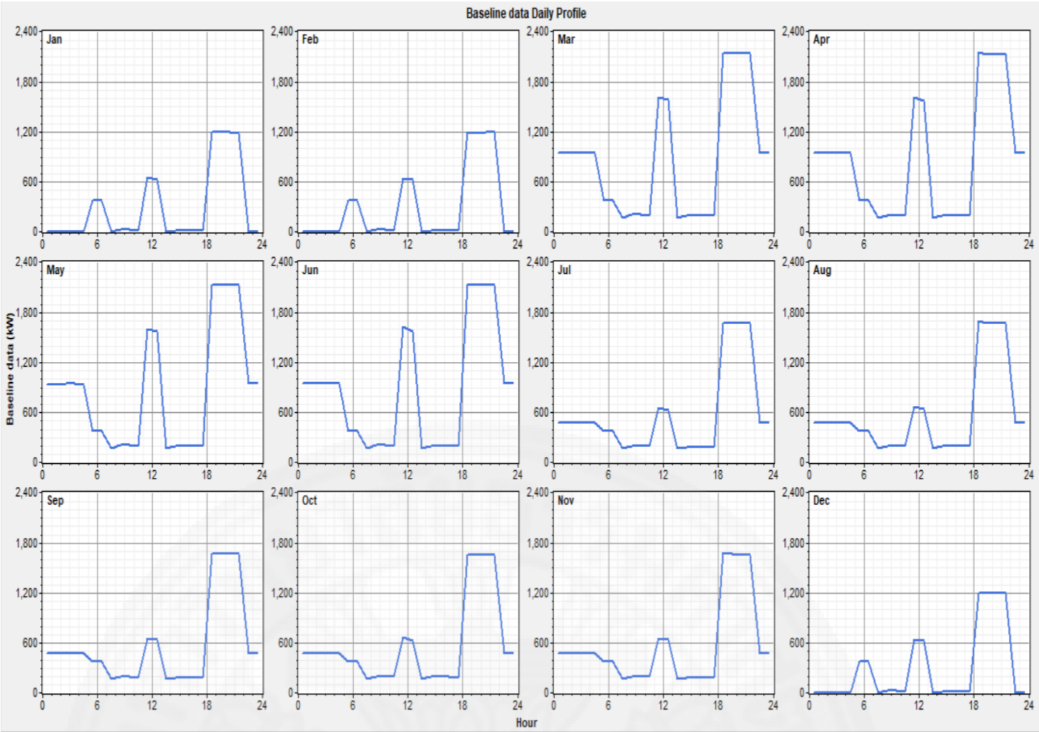


Figure 6.2 Daily profile of district load obtained from HOMER

### 6.2 Results from off-grid option

It is noticed that the results of the off-grid option have been performed in (Lao & Chungpaibulpatana, 2017). However, those results are still preliminary and need to be further developd. By this mean, different narrow step sizes of the system components (as shown in Appendix E) are used to figure out the optimal solutions. These can help the modeler better understand the feasibility of an energy plan. The running time is increased and a better specification of computer is needed. However, the methodology as well as selected scenarios is still the same and can be employed in any rural area of Cambodia.

#### 6.2.1 Diesel-only scenario

This scenario is considered as a base case by assuming that the load consumption in the district is still supplied by diesel generators. As seen from Table 6.1, the diesel-only scenario is the most expensive system for electric power generation. The total NPC and the COE of the system are around $18,322,000 and

$0.415/kWh, respectively. This scenario is the highest fuel consumption scenario which accounts for 1,906,000 liters of diesel fuel.

### 6.2.2 Diesel/PV scenario

From Table 6.1, the hybrid diesel/PV scenario ranks second by total NPC sorts. The total NPC and the COE of the system are $18,006,000 and $0.408/kWh, respectively. The renewable fraction is 5%, while fuel consumption is 1,826,000 liters or 4.4% less than the diesel-only scenario. This is due to the energy supply from solar PV to support the load in daytime.

### 6.2.3 Diesel/PV with battery scenario

As shown in Table 6.1, hybrid diesel/PV with battery is the optimum scenario. The total NPC and COE of the system are $16,570,000 and $0.375/kWh, respectively. For this scenario, the diesel fuel consumption is only 1,611,000 liters or 18.31% less than the diesel-only scenario. This diesel consumption is the lowest scenario in terms of economic consideration. This is because of the existence of solar PV panels and batteries storage which contribute to the power supply.

Table 6.1 Categorization of optimal solutions for off-grid option

| Scenarios | PV (kW) | Gen1 (kW) | Gen2 (kW) | Gen3 (kW) | Number of Battery S6CS25 | Converter (kW) | Total NPC (x$1,000) | Diesel (*1000L) | COE ($/kWh) | RF (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Diesel-only** | | 1500 | 750 | 300 | 200 | 200 | 18,322 | 1,906 | 0.415 | 0 |
| **Diesel/PV** | 200 | 1500 | 750 | 300 | - | 100 | 18,006 | 1,826 | 0.408 | 5 |
| **Diesel/PV + battery** | 600 | 1000 | 750 | 500 | 160 | 300 | 16,570 | 1,611 | 0.375 | 16 |

### 6.2.4 GHG emission deduction

As we can see from Table 6.2, the dominant pollutant gas in the power generation is carbon dioxide. The diesel-only scenario is the most pollutant scenario among others. This scenario emits almost 5,020 tons/yr of carbon dioxide and 135 tons/yr of other polluting gases. If the hybrid systems are deployed, the hybrid diesel/PV and diesel/PV with battery can eliminate around 211 tons/yr and 776 tons/yr of carbon dioxide, respectively. For other polluting gases, hybrid diesel/PV and diesel/PV with battery can reduce by about 6 tons/yr and 21 tons/yr, respectively.

Table 6.2 GHG emission from each off grid scenarios

| **Gas pollution ( kg/yr)** | **Diesel-only** | **Hybrid diesel/PV** | **Hybrid Diesel/PV with battery** |
|---|---|---|---|
| Carbon dioxide | 5,019,471 | 4,808,377 | 4,243,118 |
| Other polluted gas | 135,332 | 129,641 | 114,401 |
| Deduction of carbon dioxide | - | 211,094 | 776,353 |
| Deduction of other polluted gas | - | 5,691 | 20,931 |
| **Total deduction gas** | - | 216,785 | 797,284 |

### 6.2.5 Sensitivity analysis

#### 6.2.5.1 Variation of diesel prices and interest rates

From Figure 6.3, the diesel prices are varied from 0.6 $/liter to 1.5 $/liter. When diesel prices increase, both levelized COE and total NPC proportionally increase, and vice versa. When the diesel price increases from 0.9$/liter to 1.5$/liter, total NPC increases from 16,570,067$ to 25,056,460$ or 51.2%. Consequently, the levelized COE also increases by a similar margin from 0.375$/kWh to 0.567$/kWh. Therefore, diesel price has significant effects on the total NPC and levelized COE.

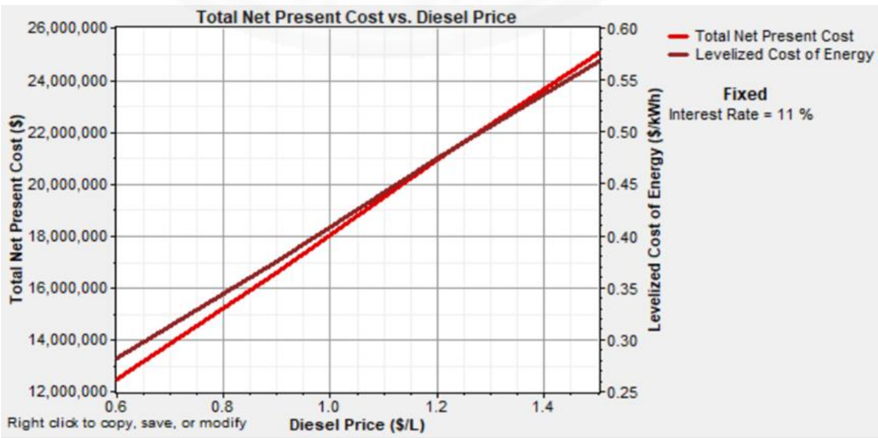


Figure 6.3 Effect of diesel price on total NPC and levelized COE

From Figure 6.4, the interest rate is varied from 6% to 15%. As we can see, when the interest rate decreases from 11% to 6%, the total NPC will increase 44.3% from 16,570,067 $ to 23,916,740$. On the other hand, the levelized COE of the system only decreases 4.8%, from 0.375 $/kWh to 0.359 $/kWh. In conclusion, the total NPC is significantly affected by the interest rate of the project, but the COE of the system is slightly affected with the changing of interest rates.

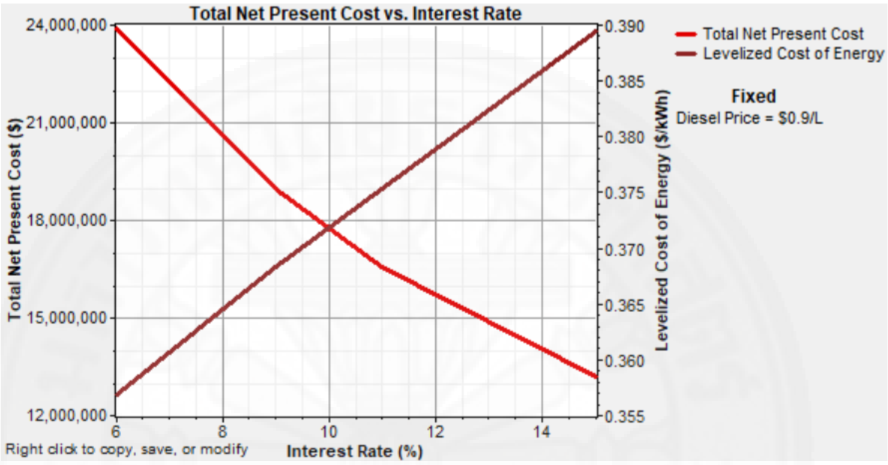


Figure 6.4 Effects of interest rates on total NPC and levelized COE

#### 6.2.5.2 Variation of consumption loads

Figure 6.5 shows the sensitivity case of daily load consumption when it increases 1.5 times and 2.0 times from the base case. It is noticed that, when the load increases two-fold from the base case, the total NPC also increases almost twice from 16,570,000$ to 33,112,000$. This is because when the demand of electricity increases, the electric supply also increases, thereby upsize all the components. However, the levelized COE decreases by a very small margin (0.21%) from $0.37575/kWh to $0.37495/kWh. This is because the analysis is performed in the same load pattern, which has low load consumption in daytime and high load consumption in nighttime. The excess electricity from solar PV is relatively high. A similar result also found in the journal paper about the remote area in East Malaysia (Das, Tan, Yatim, & Lau, 2017).

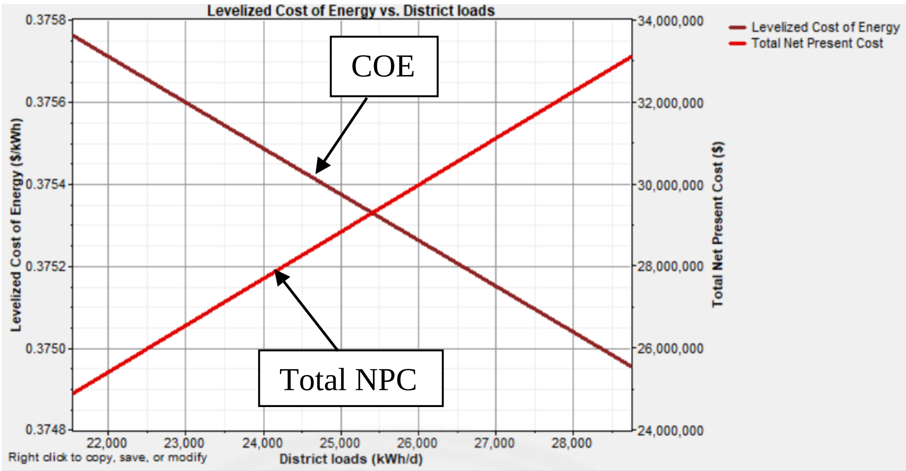


Figure 6.5 Effects of district load on COE and Total NPC

#### 6.2.5.3 Variation of solar PV component costs

Due to recent declines in solar PV components cost, sensitivity analysis of solar PV panel and battery costs are considered in this study. The costs of PV panels and batteries are varied with the capital multiplier of 0.6. By this means, the cost of solar PV panel is changing from 1500$/kW to 900$/kW and that of battery from 1,100$/unit (158.5$/kWh) to 660$/unit (95.1$/kWh). As we can see from Figure 6.6, when 40% of solar PV panels cost decreased, the total NPC and levelized COE are moderately decreased by 2.5% and 2.4%, respectively. On the other hand, when 40% of battery cost decreased, the total NPC and levelized COE are moderately increased by 0.16% and 0.27%, respectively. This is because of bigger size of batteries yield higher investment on the system. In addition, when 40% of both solar PV panel and battery costs are decreased, the total NPC and levelized COE are simutanously decreased about 3.2% compared with base case. The reason is because the low load factor of the district in daytime yields only a slight increase of renewable fraction. Therefore, if the load consumption pattern won't be changed, the excess energy from solar PV is still high. One solution would be to install more batteries to store the electricity from solar PV, but this approach will make the total NPC more expensive and therefore larger size of battery is negligible in the consideration.

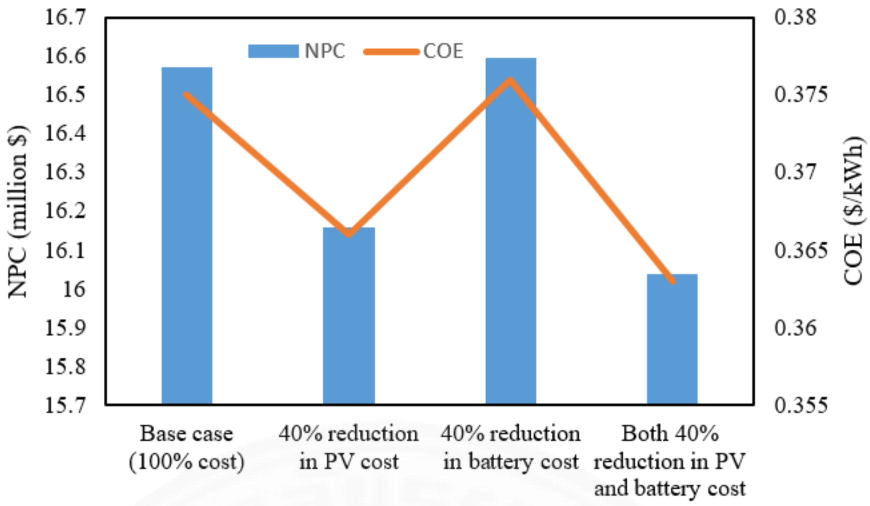


Figure 6.6 Effects of PV component costs on total NPC and COE

### 6.3 Results from on-grid option

In Cambodia, the solar PV business is still decentralized, which means that solar PV power producers can only use their own electricity, but selling to other suppliers or feeding into the national grid is still prohibited. For large scale solar farm, the power producers need to have Power Purchase Agreement (PPA) with EDC, in order to sell electricity to power grid. There is a plan for the national grid to extend to the district in the future; therefore, on-grid systems need to be considered in future energy planning.

Two cases of electric market situation are considered:

1). The government doesn't buy electricity back from solar PV, so the sales capacity to the national grid is zero.

2) The government has the policy to support renewable energy generation. Net-metering and Feed-in tariff are introduced in this study for the purpose of renewable supporting analysis.

It is noticed that, because of the low cost of the national grid (future price) as well as the low load factor in day time, the solar penetration with national grid is still low. Therefore, solar PV with installed capacity of 500 kW is proposed, in order to see the effects of solar PV penetration with the national grid as well as the implementation of the policies.

### 6.3.1 Grid-only scenario

Grid-only is another base case scenario for power system planning in this study. It is assumed that rural electricity enterprises will abandon the conventional diesel generators and start buying electricity from the national grid to supply local communities. As shown in Figure 6.7, the grid system only supplies enough energy to satisfy the load; there is no excess energy or unmet load in this scenario. From Table 6.3, the grid-only scenario is the optimal scenario for the on-grid option. The COE of the system is 0.153$/kWh with the NPC of 6,733,000 $. The Renewable fraction in the system is zero. Initial capital cost of the system is also zero due to electricity being bought from the national grid; consequently, no initial investment is required for the national grid transmission and capacity generation.

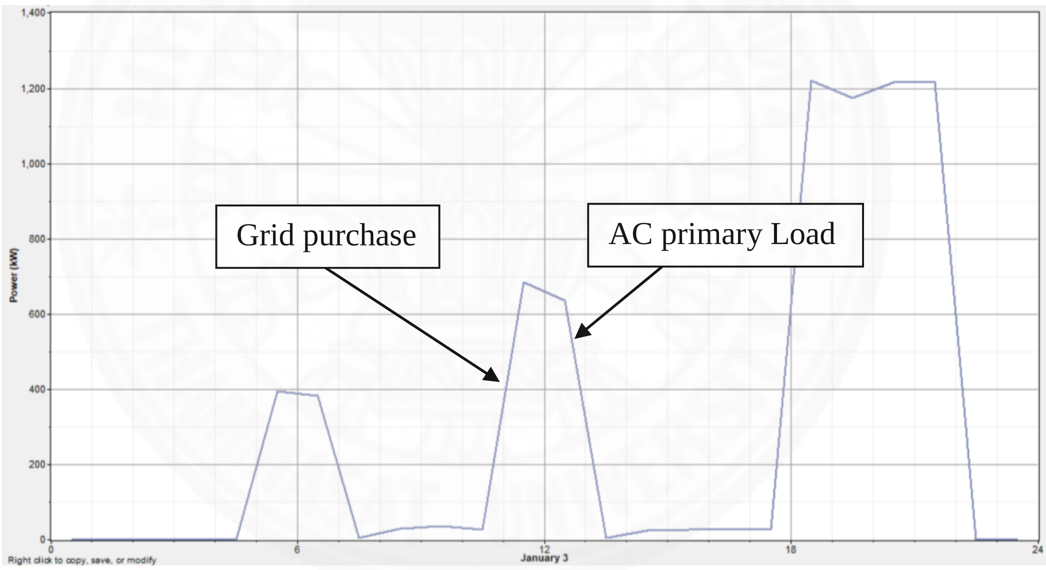


Figure 6.7 AC primary load and grid purchase pattern

### 6.3.2 Grid/PV scenario

The grid/PV scenario is the intergration of solar PV with the national grid scenario. From Figure 6.8, it can be observed that the electric power generation from solar PV is relatively low. Because of the low cost of electricity from the grid, most of the electricity is provided by the national grid. In this scenario, the excess electricity is wasted due to there being no consumption load at some points during the day. Moreover, the excess electricity cannot sell back to the national grid. From Table 6.3, the COE of the system is 0.161$/kWh with the total NPC of 7,104,000 $. The renewable solar PV fraction of the system is 13.15%. Initial capital cost of the system is 860,000 $ which mainly occurs from the solar PV component cost.

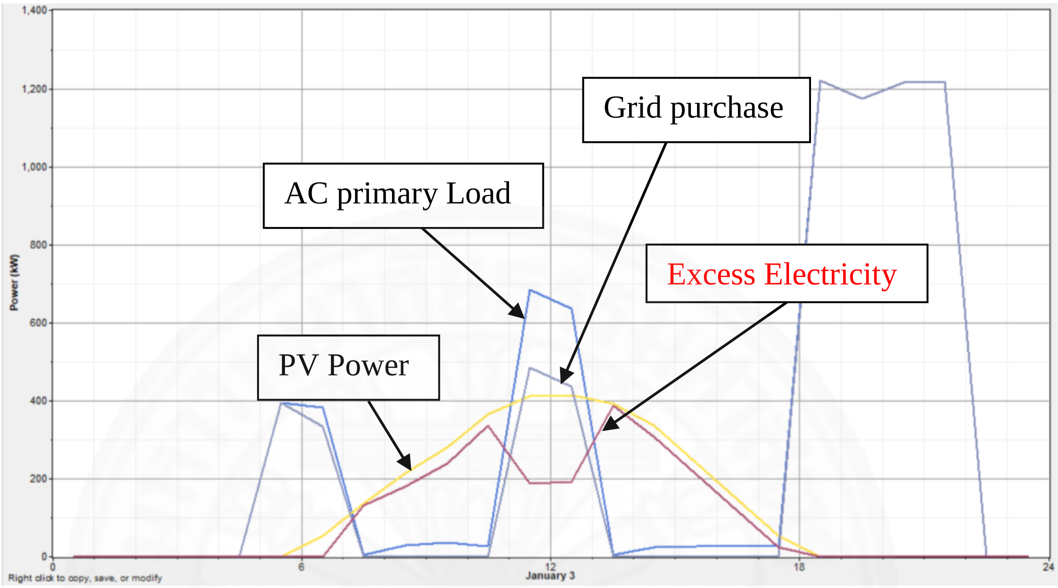


Figure 6.8 Grid/PV scenario

### 6.3.3 Grid/PV with battery scenario

As shown in Figure 6.9, the electric power from solar PV is still too low to cover the load demand during the day. This is because most of the power demand is supplied by the low cost grid system and the size of the battery also contributes to the increment of the NPC. Therefore, this scenario is less popular due to the economic problem. From Table 6.3, total NPC is 7,324,000$ and the COE of the system is 0.166$/kWh which is the highest scenario in the on-grid option. The solar PV share in the total electric generation is 13.30%.

Table 6.3 Optimal solutions of on-grid option without supporting schemes

| Scenarios | PV (kW) | Number of Battery S6CS25 | Conv (kW) | Grid (kW) | Initial capital (x$1,000) | Operating cost (x$1,000/yr) | Total NPC (x$1,000) | COE ($/kWh) | RF (%) |
|---|---|---|---|---|---|---|---|---|---|
| **Grid-only (Base case)** | - | - | - | 2400 | - | 800 | 6,733 | 0.153 | 0 |
| **Grid/PV** | 500 | - | 200 | 2400 | 860 | 741 | 7,104 | 0.161 | 13.15 |
| **Grid/PV +battery** | 500 | 200 | 200 | 2400 | 1,080 | 742 | 7,324 | 0.166 | 13.30 |

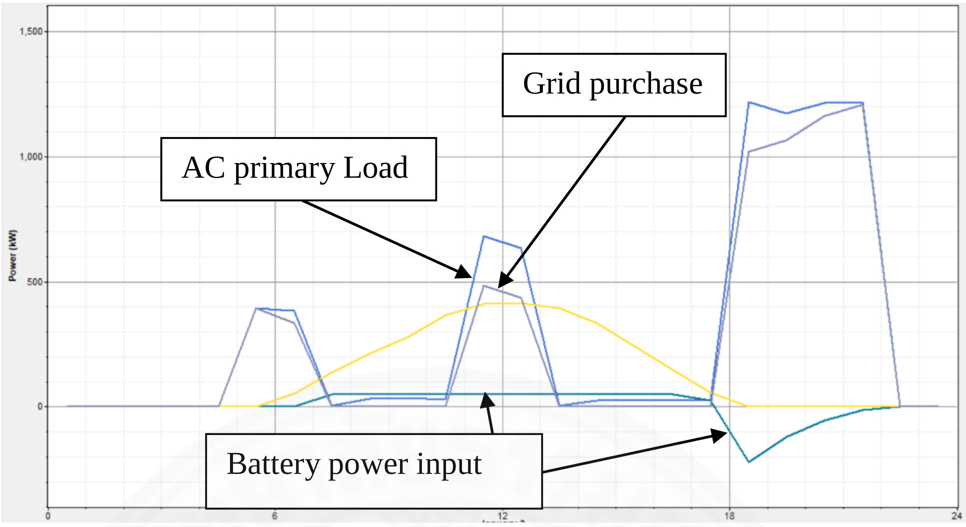


Figure 6.9 Grid/PV with battery as back up

### 6.3.4 Carbon dioxide emission

Carbon dioxide emission analysis has been carried out by using the estimation of national grid emission factor in the year 2015, from the previous chapter. As we can see from Figure 6.10, the grid-only scenario is the most polluted scenario with 758t/yr of carbon dioxide emission. Comparing with grid-only scenario, carbon dioxide emission is significantly decreased for both grid/PV and grid/PV with battery scenarios. The annual avoided carbon dioxide emission from Grid/PV and Grid/PV with battery are 66 tons and 68 tons, respectively. Therefore, the contribution of renewable energy in the grid system plays an important role for carbon dioxide mitigation.

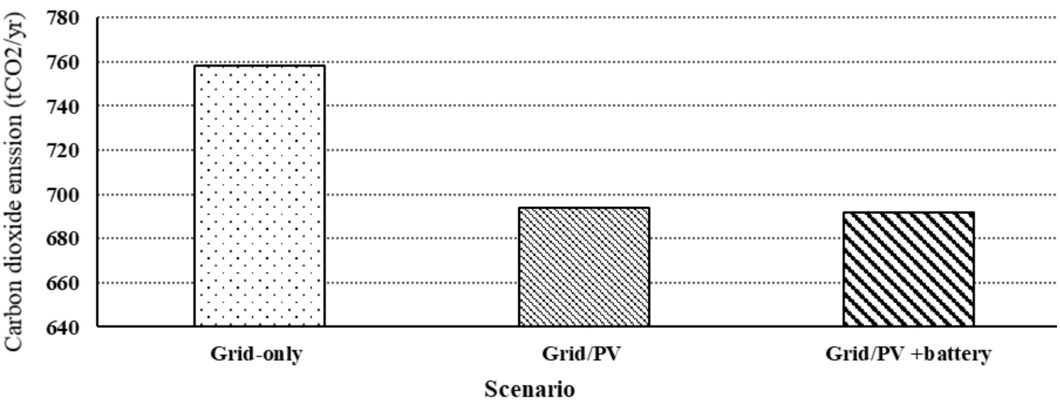


Figure 6.10 Carbon dioxide emission from each scenario

### 6.3.5 Renewable supporting schemes

As mentioned above, solar PV penetration with national grid is more expensive than a conventional grid-only system. Therefore, supporting schemes such as Net-metering and Feed-in tariff are introduced in this study.

#### 6.3.5.1 Net-metering

For net-metering, it is assumed that any excess electricity from daytime consumption will feed into national grid. The utility will charge the users only the net purchase of power from the grid. Table 6.4 shows the results of each scenario in net-metering basis. It can be seen that both total NPC and COE of all hybrid systems are decreased if compared with the same scenario in the non-net metering scheme. Moreover, the initial capital cost as well as operating cost are also lower. This is due to the deduction of net purchases from the grid by integrating the solar PV into the power generation.

Table 6.4 Optimal solutions in net-metering supporting scheme

| Scenarios | PV (kW) | Number of Battery S6CS25 | Conv (kW) | Grid (kW) | Initial capital (x$1,000) | Operating cost (x$1,000/yr) | Total NPC (x$1,000) | COE ($/kWh) | RF (%) |
|---|---|---|---|---|---|---|---|---|---|
| **Grid-only (Base case)** | - | - | - | 2400 | - | 800 | 6,733 | 0.153 | 0 |
| **Grid/PV** | 500 | - | 300 | 2400 | 915 | 713 | 6,918 | 0.157 | 13.25 |
| **Grid/PV +battery** | 500 | 200 | 200 | 2400 | 1,080 | 728 | 7,213 | 0.163 | 13.30 |

#### 6.3.5.2 Feed-in tariff

One of the common renewable energy supporting schemes is a feed-in tariff, which means that the government will buy excess electricity from users at a certain rate to encourage people to utilize electric power from renewable resource. Generally, this scheme is applied when renewable energy generation is economically uncompetitive with a conventional grid system. Sensitivity analysis of sellback rates is carried out to find the minimal feed-in tariff in our renewable energy project.

From Figure 6.11, feed-in tariffs are varied from 0.35$/kWh to 0.42$/kWh for the purpose of finding the minimal feed-in tariff. The total NPC of the hybrid systems needs to be equal to or less than the grid-only scenario in order to be competitive. In this study, the minimal tariffs for Grid/PV and Grid/PV with battery are 0.365$/kWh and 0.406 $/kWh, respectively. At these rates, the total NPC of the hybrid systems is equal with the total NPC of the grid-only scenario. Therefore, the Cambodian government should consider these tariffs, in order to promote renewable power generation in the district as well as to reduce the reliance of unclean national grid electricity.

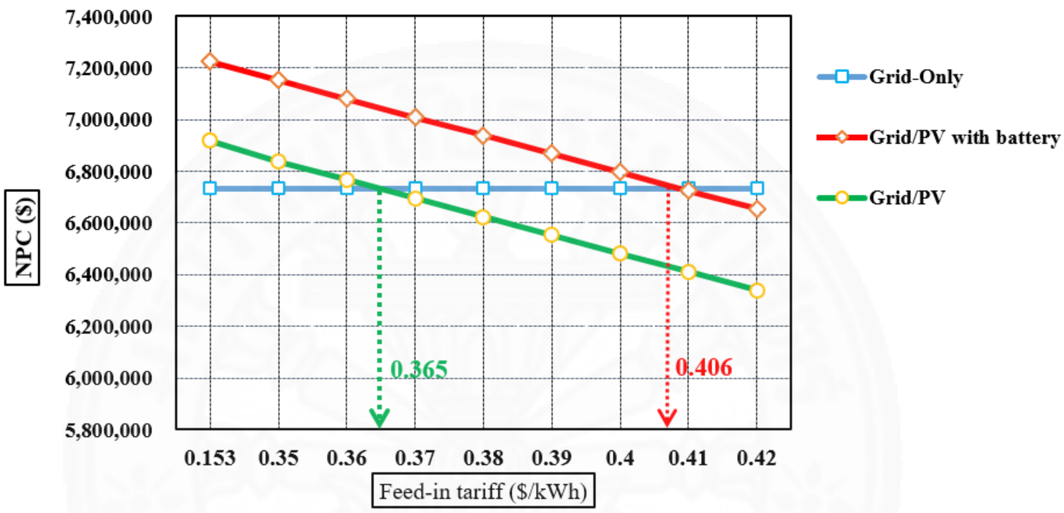


Figure 6.11 Minimal feed-in tariff for renewable hybrid systems

### 6.3.6 Sensitivity analysis

#### 6.3.6.1 Effects of solar PV lifetime on COE and NPC

Figure 6.12 demonstrates the impact of solar PV's lifetime on the total NPC and COE of grid/PV and grid/PV with battery scenarios. Grid/PV is more economical than grid/PV with battery under all investigated lifetimes. It is noticed that, when the solar lifetime of PV becomes shorter from 25 years to 15 years, both total NPC and COE of the systems just only increase by 5%. This is because of the low cost of electricity from national grid, therefore energy share from solar penetration is still low. In addition, the pattern of the load also contributes to proportion of renewable fraction too.

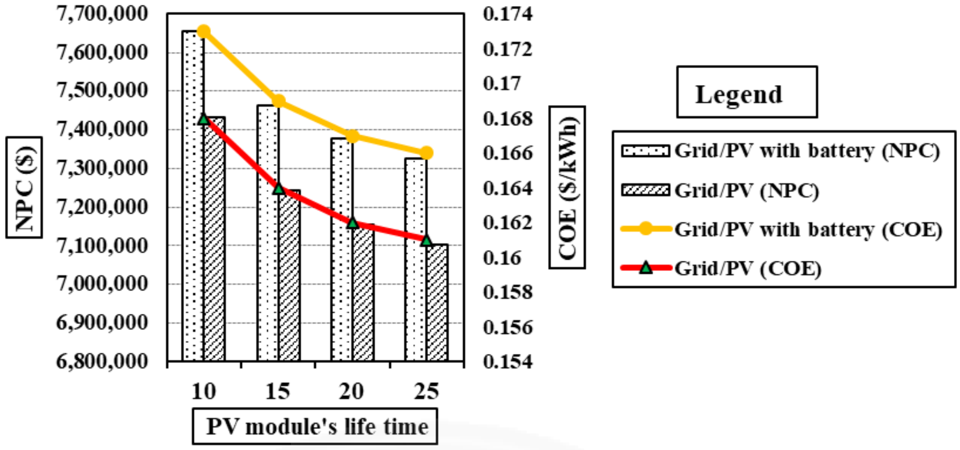


Figure 6.12 Sensitivity of PV module's lifetime

**6.3.6.2 Effects of solar penetration on NPC and carbon emission**

As we can see from Figure 6.13, minimum solar PV penetration in the total electric generation are varied from 20% to 50%. The higher PV penetration results in higher total NPC but lower carbon dioxide emission. Therefore, it is inevitable that we will decrease NPC if we increase the installed capacity of solar PV generation in the total share. However, by deployment of green energy from solar PV, the carbon dioxide emission in the national grid will considerately decrease. Therefore, this is crucial for energy planners to consider and weight properly for both parameters.

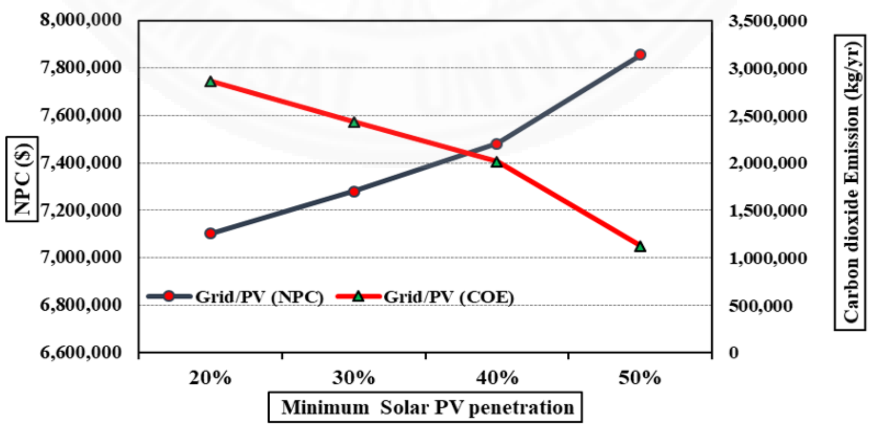


Figure 6.13 Sensitivity of minimum solar PV penetration

# Chapter 7
# Conclusions and recommendations

In this thesis, two main electrical power supplying options have been investigated with six scenarios of different configuration. These two options comprise both off-grid and on-grid scenarios. This chapter presents the conclusion of the findings from this thesis as well as the recommendations for the promotion of solar PV utilization in Cambodia.

## 7.1 Off-grid power generation scenarios

For off-grid power generation scenarios, diesel/PV with battery system is the optimum scenario. The total NPC and COE of the system are 16,570,000$ and 0.375$/kWh, respectively. The renewable fraction of the system is 16%. Compared with the diesel-only scenario, the system can eliminate about 776 tons/year of carbon dioxide as well as 21 tons/year of other pollutant gases. Diesel fuel consumption can be lowered by 18.31% with this scenario. For sensitivity analysis, the total NPC is sensitive with the changing of the consumption loads. The larger consumption loads result in a higher NPC. However, the COE of the system is only slightly affected by these parameters. This is due to the load pattern of the district which has a low load factor in daytime. In addition, more carbon emission can be eliminated if more renewable power generation can be deployed to the district.

## 7.2 On-grid power generation scenarios

For on-grid power generation scenarios, grid-only is the optimal scenario in terms of economic consideration. The total NPC and COE of the system are 6,733,000$ and 0.153$/kWh, respectively. The renewable fraction in this scenario is zero. However, this scenario is the most polluted scenario with the emission of 758 tons of carbon dioxide per year. Therefore, renewable penetration to national grid system is preferable for the planning. The grid/PV scenario is the second optimal solution for the district. The total NPC and COE are 7,104,000$ and 0.161$/kWh, respectively. On the other hand, because of the low cost of the national grid system for supplying the nighttime load, grid/PV with battery scenario is less dramatic in terms of economic consideration. In addition, it is noticed that the renewable supporting schemes have the sensitive effects on the total NPC and COE of the hybrid renewable energy systems. By the implementation of net-metering, the total NPC and COE of the Grid/PV system are reduced by 6,918,000$ and 0.157$/kWh, respectively. For the feed-in tariff consideration, in order to make the proposed hybrid scenarios become more competitive, the minimal feed-in tariff of grid/PV and Grid/PV with battery needs to be not less than 0.365$/kWh and 0.406$/kWh, respectively. In addition, the implementation of renewable supporting schemes would also contribute to the reduction of the total NPC and COE if compared with the same scenarios in normal cases.

In conclusion, even though the study focuses only on Prasat Sambour district, the methodology for rural electrification planning of this study can be applied to other districts or rural areas in Cambodia. It can help investors and designers during the preliminary design process as well as with the planning of rural electrification. Therefore, solar energy, a clean energy technology with zero carbon emission in generation, will accelerate the energy transition of the country in the near future.

### 7.3 Recommendations for rural electrification development plan

Even though renewable energy is a key to Cambodian rural electrification development plans, implementation of solar energy in electric power generation is still minimal. Below are some recommendations for the government:

- Consider supporting policies or incentives in order to promote the renewable energy projects in Cambodia.
- Open a free market in the electricity sector to allow power producers and end users to independently sell or buy electricity.
- Provide some financial loans to rural electricity enterprises that use renewable resource for generating electricity.
- Set a clear renewable energy road map in the national power development plan.
- Reduce import tax on renewable energy equipment such as batteries, solar PV modules or power electronic control devices.

## 7.4 Recommendations for future research work

This thesis mainly focuses on rural electrification planning. The further research work to be considered is recommended as follows:

- Validation of the latest local demand or load data if available, in order to make the system configuration more reliable.
- Energy consumption should be considered in sectors other than residential and public sectors.
- For infrastructure planning, system stability as well as control operation of the renewable energy system penetration with the national grid should be included in the investigation.
- Energy efficiency scenarios should be taken into account for the modern implementation in the district
- Run simulations with different software and compare the obtained results.
- A high speed computer for running the simulation and a more precise component step-size in the search space should be considered.

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**Appendices**

# Appendix A

## Questionnaire in English Version

This questionnaire is aimed to survey current and future demand loads of electricity in Prasat Sambour district, Kampong Thom. The results are aimed to help energy planning stakeholders for a better understanding of electricity demand and also prepare for the future development.

If you have any quarries, please kindly contact me via:

Tel: (+66) 95 010 3515, email: chhunhenglao@gmail.com.

### I. General detail:

| | |
|---|---|
| 1. Name of interviewee: | 2.Home types: ☐ Brick ☐ Wood with tile roof<br>☐Thatch house ☐Others_____________ |
| 3. Number of family's members: _______ | 4. Main occupation: __________________ |
| 5. Do you buy electricity from local electric supplier?<br>☐Yes: Monthly expense on electricity: ____________________<br>Month that electric bill cost the most: ________________ (continue II) | |
| ☐ No | |
| **6. Solar Home System**:_______Wp | |
| **7. Battery**: *Capacity*: ____________Ah *Price*:_______________Riel | |
| *Number of charges*: _____/week, *Price charge*: _______________Riel/ battery | |
| 8. **Kerosene**: *Weekly consumption of kerosene*:____________liter/week | |
| *Expense on kerosene*:__________Riel/liter | |

### II. Current electricity

| Electric appliances | Estimate Power (W) | Quantity | Time of use |
|---|---|---|---|
| 18W CFL | **18** | | |
| 36W CFL | **36** | | |
| Incandescent Lamp | **75** | | |
| 16 inches electric fan | **50** | | |
| 18 inches electric fan | **70** | | |
| 20 inches color TV | **75** | | |
| 14 inches color TV | **60** | | |
| VCD player | **25** | | |

## III. Basic daily information

3.1. How many livestock do you have?

| | Cow | Buffalo | Pig | chicken | duck |
|---|---|---|---|---|---|
| Number of livestock | | | | | |

3.2. How do you use the livestock manure?

☐Fertilized rice field or farm ☐ Sell to middle man ☐Uncollected

☐ Others: __________

3.3. What kind of fuel do you use for cooking?

☐Wood ☐Charcoal ☐ LPG ☐biogas ☐Others:_____________

3.4. Is it convenient to use such kind of cooking?

☐Yes ☐No, Reason:_______________

3.5. What is the main source of water for drinking and daily use?

☐Well or Pound ☐ Own water pump ☐ nearby river

☐ Others (please specific) ____________

3.6. Do you have any problem in obtaining the water?

☐Yes **Reason** ☐ too far ☐No water (drought, dry season) ☐ Others_________

☐ No

3.7. Does your family' s member used to get disease by using unclean water, or recent sick?

☐ Yes Male: Female: Name of Disease:

☐ No

## IV. Future electricity

When the electric tariff is declined or grid connected, preferable electric appliances are:

| Electric appliances | Estimate Power (W) | Quantity | Time of use |
|---|---|---|---|
| Rice cooker | **550** | | |
| Electric kettle | **1,500** | | |
| Clothes iron | **1,000** | | |
| Water pump (1 hp) | **735** | | |
| Irrigation pump (2 hp) | **1,470** | | |
| 6 cubic feet fridge | **90** | | |
| Air conditioner | **735** | | |

4.1. If there is a support scheme from government to promote tourism sector in the district, would you like to run a homestay for tourists?

☐Yes ☐No

## A2. Results

### I. General detail:

1.1. House type of the selected households

| | Chhuk | Sambour | Tang krasau | Koul | Srueng |
|---|---|---|---|---|---|
| Brick | 1 | 6 | 0 | 0 | 0 |
| Wood | 15 | 14 | 21 | 2 | 5 |
| Thatch | 5 | 2 | 2 | 8 | 10 |
| Others | 4 | 3 | 2 | 0 | 0 |
| **Total** | **25** | **25** | **25** | **10** | **15** |

1.2. Average family members: 5 people

1.3.Main occupation: farmers (96%)

1.4.Power generation source in selected households

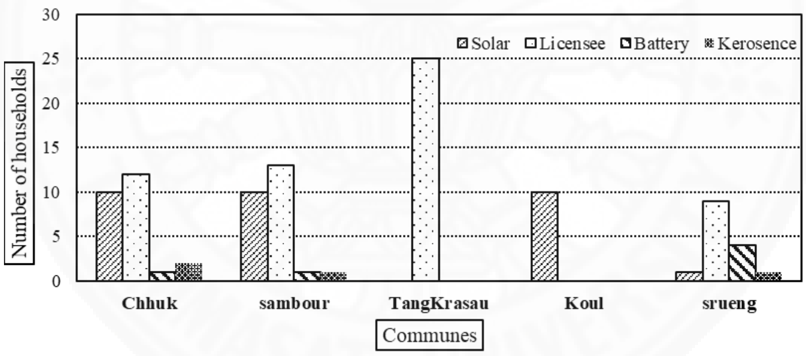



Figure A.1 Various power generation source in selected households

1.5.Electricity Expenditure in selected households

| Electricity supplying source | Amount of expenditure |
|---|---|
| **Rural electricity enterprise** | - 20,000-40,000 Riel/ month (5-10$/month) |
| **Solar Home System (SHS)** | - 24,000 Riel/$W_P$ (6$/$W_P$) Include all SHS components cost |
| **Battery** | - Capacity: 50Ahr<br>- Charge: 3 times/week (2,000riel/charge)<br>- Expense: 2.5 $/ kWh |
| **Kerosene** | - 2 Liter/week<br>- Expense: 5,600/week |

## II. Current Load profile of selected household

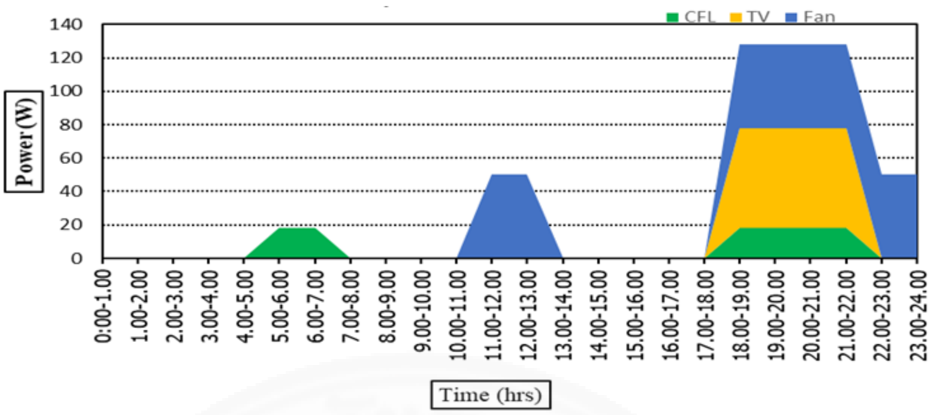



Figure A.2 Daily load demand from households

## III. Basic daily information

3.1. Average livestock in one household

| **Type of livestock** | **Cow** | **Buffalo** | **Pig** | **chicken** | **duck** |
|---|---|---|---|---|---|
| Number of livestock | 2 | 0 | 2 | 4 | 2 |

3.2. How do you use the livestock manure?

☐Fertilized rice field or farm ☐ Sell to middle man

☐Uncollected ☐ Others: ___________

**Answer**: All of the households that have livestock said that, they use livestock manure for fertilizing their rice field or farm.

3.3. What kind of fuel do you use for cooking?

☐Wood ☐Charcoal ☐ LPG ☐biogas ☐Others: ______________

**Answer**: Most of households use wood that they can find in the forest to be a cooking fuel source.

3.4. Is it convenient to use such kind of cooking?

☐Yes ☐No, Reason: ________________

**Answer:** Not really, because they need to spend a lot of time to find. Nevertheless, they are still using it since it's free and available.

3.5. Does your family's member used to get disease by using unclean water, or recent sick?

☐ Yes Male: Female: Name of Disease:

☐ No

**Answer**: 99% said No, 1% said Yes (some skin disease)

## IV. **Future electricity**

Majority of the households want to use rice cooker and irrigation pump if their locations are connected to grid in a reasonable price.

| **Electric appliances** | **Estimate Power (W)** | **Quantity** | **Time of use** |
|---|---|---|---|
| Rice cooker | **550** | 1 | 6:00-6:30 am,<br>11:00-11:30 am<br>5:30-6:00 pm |
| Electric kettle | **1,500** | | |
| Clothes iron | **1,000** | | |
| Water pump (1 hp) | **735** | | |
| Irrigation pump (2 hp) | **1,470** | 1 | 7:00-10:00 am |
| 6 cubic feet fridge | **90** | | |
| Air conditioner | **735** | | |

4.1.If there is a support scheme from government to promote tourism sector in the district, would you like to run a homestay for tourists?

☐Yes ☐No

**Answer**: Some households want to run the homestay if there are any supporting schemes from government to promote tourism sector in the district. For poor households, they don't want to run any homestay.

# Appendix B

## Primary data collection

1. <u>Site visit to Kampong Chhuerteal institute of technology</u>

Figure B.1 Meet with vice-director of the institute

Figure B.2 Visit solar rooftop project in the institute

2. **<u>House types in surveying site</u>**

Brick house

Wooden house

Wooden house with SHS

Thatch house

Figure B.3 House types in survey site

## 3. Site survey

Figure B.4 Site survey with questionnaire interview

4. Data collection and preparation

Figure B.5 Data collection and team discussion

5. Survey team for residential load consumption of Prasat Sambour district


Figure B.6 Survey team

## Appendix C

### Maps of Prasat Sambour district

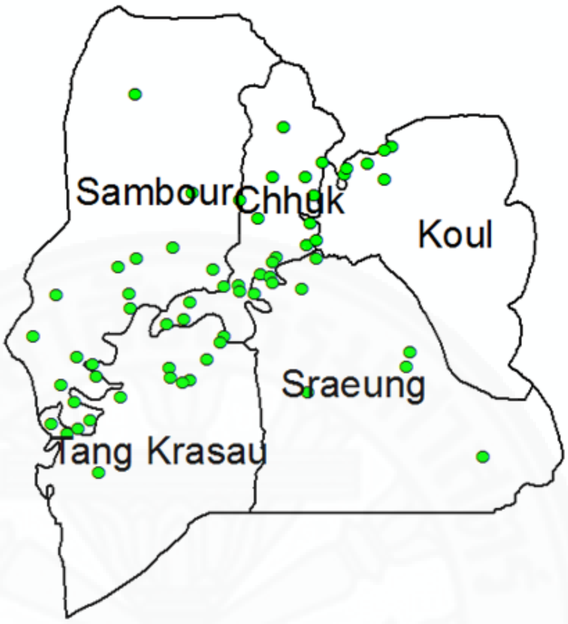



Figure C.1 Map of the villages in Prasat Sambour

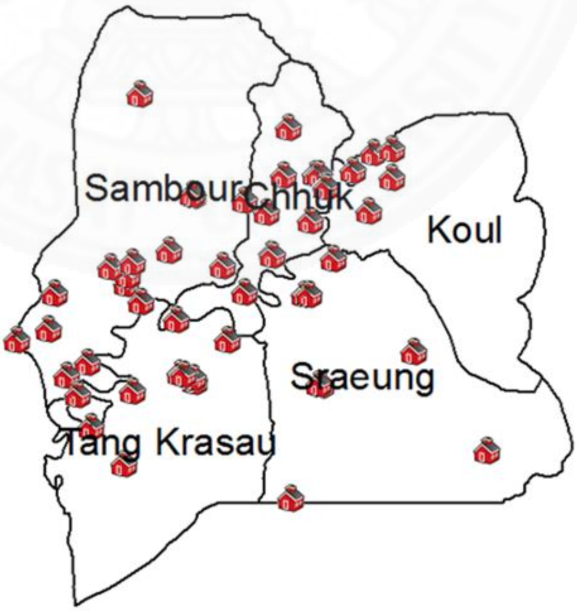



Figure C.2 Map of the schools in Prasat Sambour

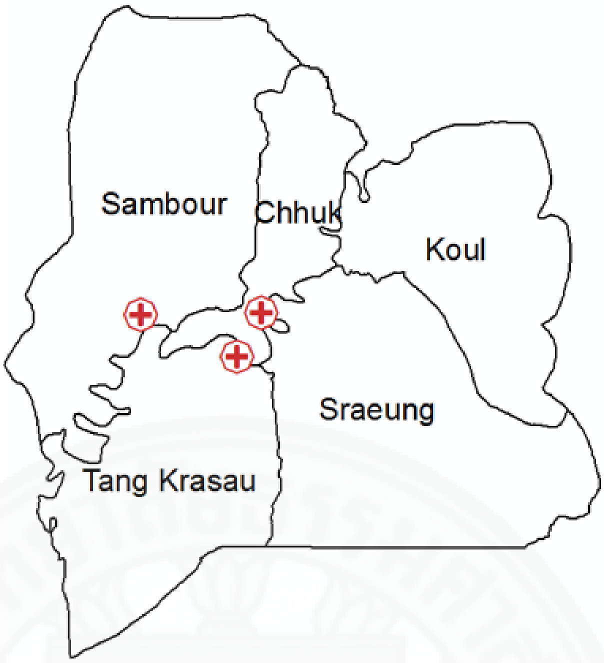



Figure C.3 Map of the health centers in Prasat Sambour


Figure C.4 Map of the watershed in Prasat Sambour

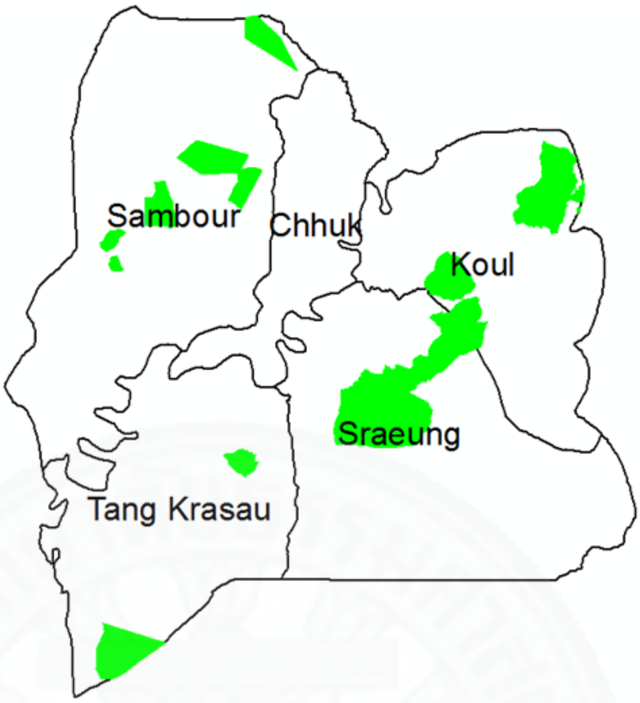



Figure C.5 Map of the community forest in Prasat Sambour

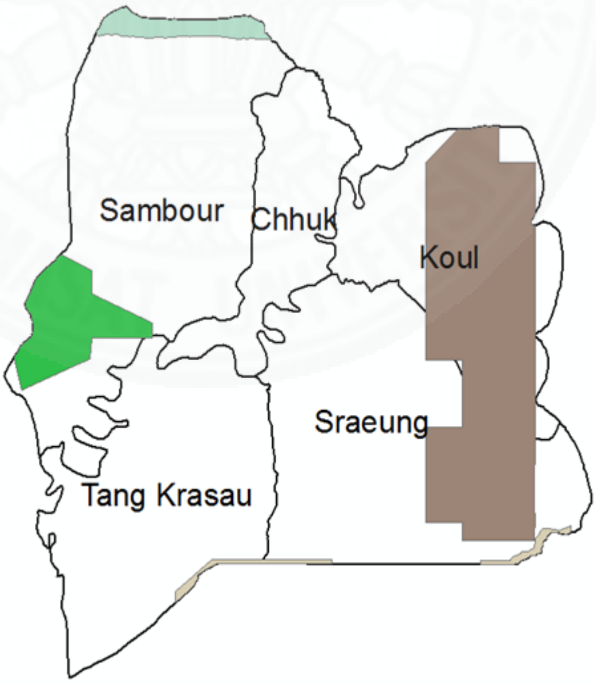



Figure C.6 Map of the Land concession and protected areas in Prasat Sambour

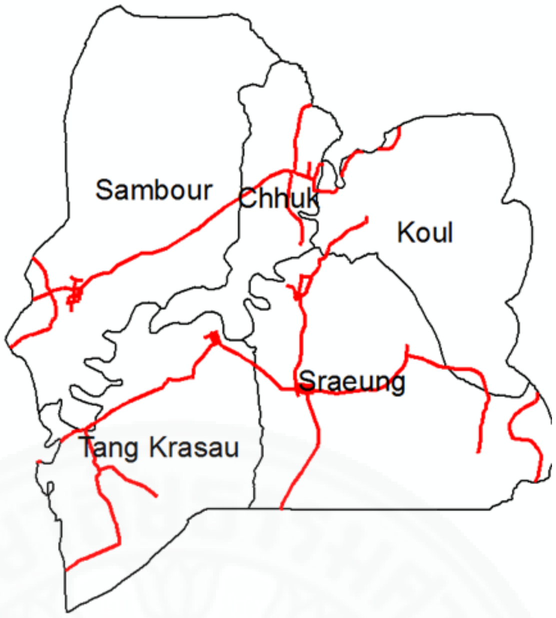



Figure C.7 Map of the main roads in Prasat Sambour

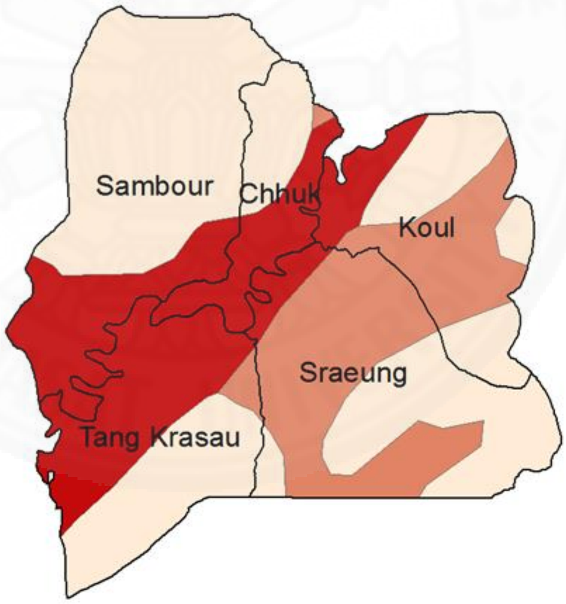



Figure C.8 Map of the soil types in Prasat Sambour

# Appendix D

Primary demand load in Prasat Sambour

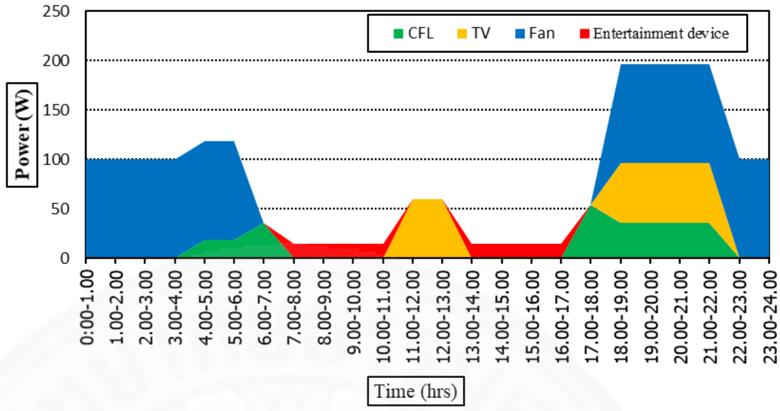



Figure D.3 Daily load profile of one residential house

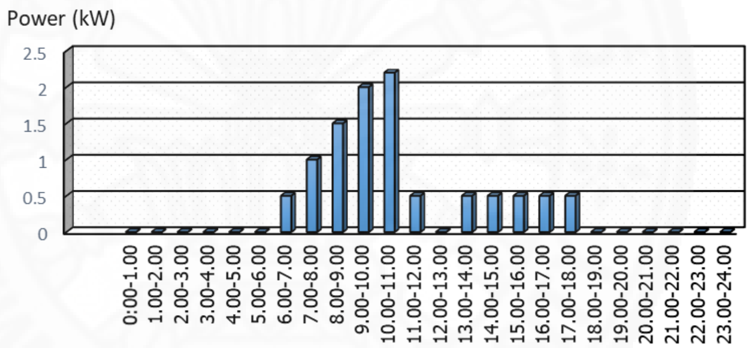



Figure D.2 Daily load profile of one health center

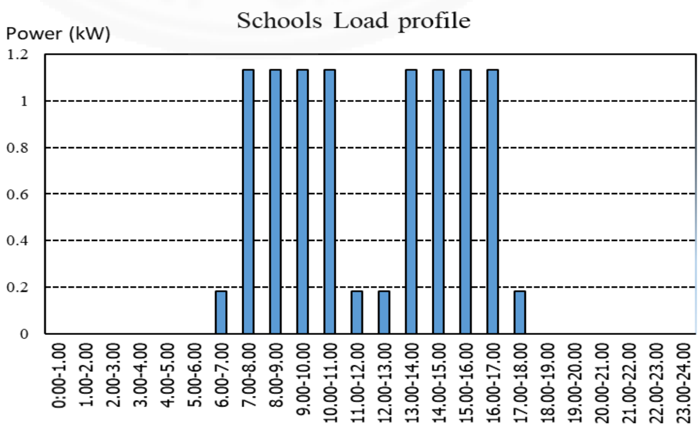


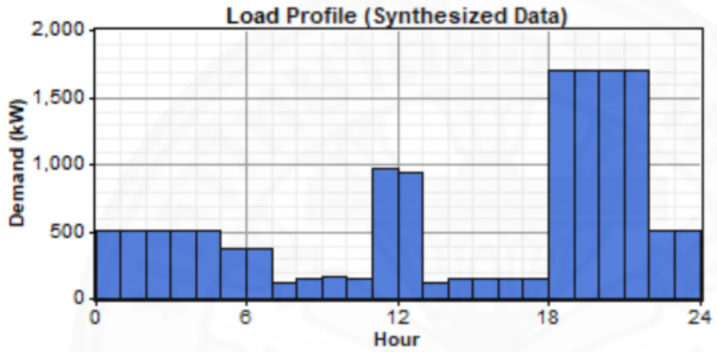

Figure D.3 Daily load profile of one school

# Appendix E

## HOMER Input Summary

### AC Load: District loads

| | |
|---|---|
| Data source: | Synthetic |
| Daily noise: | 2% |
| Hourly noise: | 2% |
| Scaled annual average: | 14,364 kWh/d |
| Scaled peak load: | 2,323 kW |
| Load factor: | 0.258 |




### PV

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/yr) |
|---|---|---|---|
| 1.000 | 1,500 | 1,500 | 10 |

| | |
|---|---|
| Sizes to consider: | 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,100, 1,200, 1,300, 1,400, 1,500 kW |
| Lifetime: | 25 yr |
| Derating factor: | 80% |
| Tracking system: | No Tracking |
| Slope: | 12.9 deg |
| Azimuth: | 0 deg |
| Ground reflectance: | 20% |

## Solar Resource

Latitude: 12 degrees 53 minutes North
Longitude: 105 degrees 3 minutes East
Time zone: GMT +7:00

Data source: Synthetic

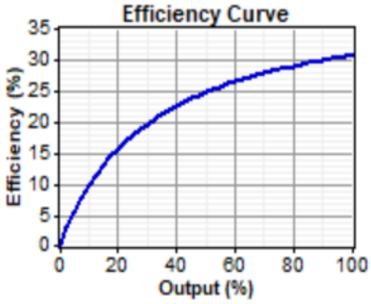
| Month | Clearness Index | Average Radiation (kWh/m²/day) |
|---|---|---|
| Jan | 0.643 | 5.470 |
| Feb | 0.638 | 5.920 |
| Mar | 0.580 | 5.850 |
| Apr | 0.566 | 5.970 |
| May | 0.527 | 5.580 |
| Jun | 0.501 | 5.260 |
| Jul | 0.488 | 5.130 |
| Aug | 0.467 | 4.900 |
| Sep | 0.457 | 4.660 |
| Oct | 0.505 | 4.790 |
| Nov | 0.578 | 5.000 |
| Dec | 0.615 | 5.060 |

Scaled annual average: 5.29 kWh/m²/d

## AC Generator: Generator 1

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/hr) |
|---|---|---|---|
| 1.000 | 500 | 450 | 0.020 |

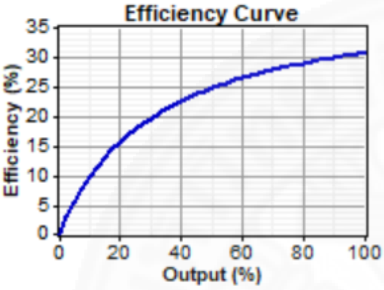
Sizes to consider: 0, 500, 1,000, 1,500, 2,000 kW
Lifetime: 15,000 hrs
Min. load ratio: 30%
Heat recovery ratio: 0%
Fuel used: Diesel
Fuel curve intercept: 0.08 L/hr/kW
Fuel curve slope: 0.25 L/hr/kW



## AC Generator: Generator 2

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/hr) |
|---|---|---|---|
| 1.000 | 500 | 450 | 0.020 |

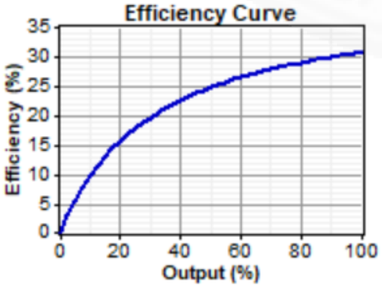
| | |
|---|---|
| Sizes to consider: | 0, 750, 1,000, 1,250, 1,750 kW |
| Lifetime: | 15,000 hrs |
| Min. load ratio: | 30% |
| Heat recovery ratio: | 0% |
| Fuel used: | Diesel |
| Fuel curve intercept: | 0.08 L/hr/kW |
| Fuel curve slope: | 0.25 L/hr/kW |




## AC Generator: Generator 3

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/hr) |
|---|---|---|---|
| 1.000 | 500 | 450 | 0.020 |

| | |
|---|---|
| Sizes to consider: | 0, 250, 300, 500, 750, 1,000, 1,250 kW |
| Lifetime: | 15,000 hrs |
| Min. load ratio: | 30% |
| Heat recovery ratio: | 0% |
| Fuel used: | Diesel |
| Fuel curve intercept: | 0.08 L/hr/kW |
| Fuel curve slope: | 0.25 L/hr/kW |




## Fuel: Diesel

| | |
|---|---|
| Price: | $ 0.9, 0.6, 1.2, 1.5/L |
| Lower heating value: | 43.2 MJ/kg |
| Density: | 820 kg/m3 |
| Carbon content: | 88.0% |
| Sulfur content: | 0.330% |

## Battery: Surrette 6CS25P

| Quantity | Capital ($) | Replacement ($) | O&M ($/yr) |
|---|---|---|---|
| 1 | 1,100 | 1,100 | 10.00 |

| | |
|---|---|
| Quantities to consider: | 0, 10, 20, 30, 40, 50, 60, 70 |
| Voltage: | 6 V |
| Nominal capacity: | 1,156 Ah |
| Lifetime throughput: | 9,645 kWh |

## Converter

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/yr) |
|---|---|---|---|
| 1.000 | 550 | 550 | 10 |

| | |
|---|---|
| Sizes to consider: | 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1,000 kW |
| Lifetime: | 15 yr |
| Inverter efficiency: | 90% |
| Inverter can parallel with AC generator: | Yes |
| Rectifier relative capacity: | 100% |
| Rectifier efficiency: | 85% |

## Economics

| | |
|---|---|
| Annual real interest rate: | 11, 15, 9, 6% |
| Project lifetime: | 25 yr |
| Capacity shortage penalty: | $ 0/kWh |
| System fixed capital cost: | $ 0 |
| System fixed O&M cost: | $ 0/yr |

## Generator control

| | |
|---|---|
| Check load following: | Yes |
| Check cycle charging: | Yes |
| Setpoint state of charge: | 80% |

| | |
|---|---|
| Allow systems with multiple generators: | Yes |
| Allow multiple generators to operate simultaneously: | Yes |
| Allow systems with generator capacity less than peak load: | Yes |

## Emissions

| | |
|---|---|
| Carbon dioxide penalty: | $ 0/t |
| Carbon monoxide penalty: | $ 0/t |
| Unburned hydrocarbons penalty: | $ 0/t |
| Particulate matter penalty: | $ 0/t |
| Sulfur dioxide penalty: | $ 0/t |
| Nitrogen oxides penalty: | $ 0/t |

## Constraints

Maximum annual capacity shortage: 0%
Minimum renewable fraction: 0%

Operating reserve as percentage of hourly load: 10%
Operating reserve as percentage of peak load: 0%
Operating reserve as percentage of solar power output: 25%
Operating reserve as percentage of wind power output: 50%

## Grid (non-supporting schemes)

| Rate | Power Price | Sellback Rate | Demand Rate | Applicable |
|---|---|---|---|---|
| | $/kWh | $/kWh | $/kW/mo. | |
| Rate 1 | 0.153 | 0 | 0 | Jan-Dec All week 00:00-24:00 |

$CO_2$ emissions factor: 145 g/kWh
CO emissions factor: 0 g/kWh
UHC emissions factor: 0 g/kWh
PM emissions factor: 0 g/kWh
$SO_2$ emissions factor: 2.74 g/kWh
$NO_x$ emissions factor: 1.34 g/kWh
Interconnection cost: $ 0
Standby charge: $ 0/yr
Purchase capacity: 2,400 kW
Sale capacity: 0 kW

## Economics

Annual real interest rate: 11%
Project lifetime: 25 yr
Capacity shortage penalty: $ 0/kWh
System fixed capital cost: $ 0
System fixed O&M cost: $ 0/yr

## Generator control

Check load following: Yes
Check cycle charging: No

Allow systems with multiple generators: Yes
Allow multiple generators to operate simultaneously: Yes
Allow systems with generator capacity less than peak load: Yes