PV-Bio Diesel from a Farmer Diesel Engine for Hybrid Solar Home Systems

A thesis submitted in partial fulfillment for the degree of Doctor of Engineering (Dr.-Ing) in the specialized area of Energy Technology at the Faculty of Electrical Engineering, University of Kassel.

By

Jiratkwin Rakwichian

Place: Kassel

Date of Disputation: 13.06.2008

Supervisors:

1. Prof. Dr.-Ing. Jürgen Schmid
2. Prof. Dr.-Ing. habil. Ingo Stadler

Erklärung

Hiermit versichere ich, dass ich die vorliegende Dissertation selbständig und ohne unerlaubte Hilfe angefertigt und andere als die in der Dissertation angegebenen Hilfsmittel nicht benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder unveröffentlichten Schriften entnommen sind, habe ich als solche kenntlich gemacht. Kein Teil dieser Arbeit ist in einem anderen Promotions- oder Habilitationsverfahren verwendet worden.

....
(Jiratkwin Rakwichian)
Place, Date of Disputation
Kassel, 13.06.2008

Abstract

The core objective study of the thesis, *"PV-Bio Diesel from a Farmer Diesel Engine for Hybrid Solar Home Systems (PV-Bio FDE for HSHS)"* is to provide the solution for the failures of 300,000 households, 120W Solar Home System (SHS) project. It is found that the problems of SHS are 1 insufficient energy supply cause of the energy demand of the users (in this work refer to Thai farmers) increasing after they have electricity used and 2 unsustainable energy supply, when its rainy and cloudy and even peak load demand are incurred. The SHS could not provide enough amount of the energy for serving extra needs of the farmers load demand like rice cooker or other more appliances use.

This work will then focus on combining the existing *"Farmer Diesel Engine (FDE)"* as normally owned by farmers with PV Array from SHS to form the hybrid system in order to generate local electricity use in their families.

According to ordinary Thai farmer families' culture and life style in rural area, they always live and build the houses close together in cluster. Each cluster consists of 3-5 households. The *"parent house"* is the one provider who coupling FDE with AC Machine by pulley welt-drive to provide electricity supplying to his 2-4 *"child house"*. To develop it to be PV-Bio FDE for HSHS follow methodology that single parent provider supplies electricity to his child family houses in neighboring would be the most suited to their life.

The prototype of PV-Bio FDE for HSHS is designed and installed to farmer families in Phichit province, which located 60 kilometers southern from Phitsanulok. The main system components consist of the old Photovoltaic Array (PV Array) 2 strings in parallel of 4 modules in series in total capacity of 424 W_p from SHS, FDE 11 with power 11 horse power (HP), AC Machine 3 kVA, Bi-directional inverter 1.5 kVA, charge controller 15 A and 4 units of batteries storage 12V_{dc} capacity 85Ah.

The system evaluation and analysis include 3 perspectives that are concluded in the following:

1. Technical performance perspectives

    - The efficiency of PV-Modules (η_{PV}) is 6%-7%.
    - The efficiency of Bi-directional inverter (η_{inv}) is about 80% – 82%.
    - The 6 months average of performance ratio (PR) is 70.60%.
    - The 6 months average of solar fraction is 69.64%.
    - The 6 months average of final yield is 3.54 hours/day.

2. Economic perspectives

   - FDE is normally owned by almost every farmer families, thus the cost of FDE is not taken into account in Life Cycle Costs (LCC) analysis. Then the payback period of the system can be shorter.
   - PV-Modules are also not counted in LCC analysis, because those modules were taken from other failed projects.
   - The total LCC (ALCC) result in analysis is 7,841.05 €
   - The total energy generated by the system is 20,984 kWh.
   - Electricity cost is 0.48 € / kWh.

3. Environmental assessment perspectives

   - Daily FDE operation hours are reduced from about 1-2 hours down to 30-50 minutes that affected correspondingly to fuel costs reduction.
   - Noise pollution hours are reduced according to operation hours.

The results from evaluation and analysis of above technical performance, economic and environmental assessment indicate that the PV-Bio FDE for HSHS is very satisfied hybrid solution for farmer family as concluded in the following:

- Technologies performance approved and well system functioning.
- System has more stability and reliability comparing to SHS.
- System Flexibility design and in line with Thai farmer social and culture.
- Farmers as the users are able to use this innovative hybrid system with low investment because system allows to use most existing power generation equipments e.g. PV-Modules from SHS, FDE and AC Machine.
- This hybrid system is able to supply the increasing farmer need of electricity when farmers would like to have more appliances for their comfort life.
- System is designed for manual operation, less complexity and easy for self maintenance by farmers.
- The use of FDE for generating electricity is regularly familiar for farmers.
- Costs of diesel fuel and noise pollution are reduced comparing to electricity generation by FDE coupling AC Machine only.

The key success of the project is PV-Bio FDE for HSHS can operate nearly similar to Thai farmer culture that one FDE can generate electricity by parent provider is able to support the whole family child households in the cluster.

Kurzfassung

Der Kern der objektiven Studie der Dissertation „PV-Bio Diesel from a Farmer Diesel Engine for Hybrid-Solar-Home-Systems (PV-Bio FDE for HSHS)“ soll eine Lösung von Problemen bei einem Solar-Home-System-Projekt bieten, bei dem 300.000 Haushalte mit einem je 120W leistenden Solar-Home-System (SHS) ausgestattet werden. Es stellte sich heraus, dass verschiedene Probleme bestehen. Zum einen tritt häufig eine unzureichende Energieversorgung in Bezug auf den Verbrauch der Nutzer auf, da sich der Energieverbrauch nach Erhalt des Zugangs zu elektrischer Energie erhöht hat (dies stützt sich auf Erfahrungen thailändischer Landwirte). Zum anderen kommt es zu unzuverlässiger Energieversorgung in Zeiten bedeckten Himmels und gleichzeitigem hohen Leistungsbedarf. In diesen Fällen konnte das SHS nicht genug Energie bereitstellen, um zusätzlichen Bedarf, z.B. zum Betrieb von Reiskochern und anderen Geräten der Landwirte.

In dieser Arbeit wird der Schwerpunkt auf die Kombination der existierenden Landwirtschaftlichen Dieselaggregate („*Farmer Diesel Engine (FDE)”*), wie sie meistens bereits bei den Landwirten in Gebrauch sind, mit den PV-Modulen des SHS gesetzt. Dadurch entsteht ein Hybridsystem, mit dem ortsnah nutzbare Elektrizität für den Bedarf der Familien erzeugt werden kann.

Traditionell leben thailändische Landwirte in netzfernen Gebieten eng zusammen in kleinen Ansammlungen von etwa 3-5 Haushalten. Dabei werden von einem „Haupthaus“ mit einem FDE und einem Generator die restlichen Häuser mit Elektrizität versorgt. Um dieses System zu einem Hybridsystem weiterzuentwickeln, ist es naheliegend, diese an die Lebensbedingungen der Menschen angepasste, vorhandene Struktur zu nutzen.

Der Prototyp eines „PB-Bio FDE for HSHS“ wurde bei Landwirten und ihren Familien in der Provinz Phichit installiert, etwa 60 Kilometer südlich von Phitsanulok. Die Hauptkomponenten sind das bereits vorhandene PV-Feld mit 2 parallelen Strings mit je vier Modulen und einer Gesamtkapazität von 424 W_{pk} des SHS, einem Dieselmotor mit 11 PS, einem Generator mit einer Leistung von 3kVA, einem bidirektionalen Wechselrichter (1,5 kVA), einem Laderegler für 15A und vier Batterieeinheiten (12V, 85Ah).

Die Evaluierung des Systems und die Analyse geschieht aus drei verschiedenen Perspektiven:

1. Technische Leistungsfähigkeit

   - Der Wirkungsgrad der PV-Module (η_{PV}) beträgt 6%-7%
   - Der Wirkungsgrad des Wechselrichters (η_{inv}) beträgt ca. 80%-82%

- Das sechsmonatige Mittel des Qualitätsfaktors (performance ratio (PR)) beträgt 70,60%
- Das sechsmonatige Mittel des Solaren Deckungsanteils (solar fraction) beträgt 69,64%
- Das sechsmonatige Mittel des spezifischen Energieertrages (final yield) beträgt 3,54 Stunden/Tag

2. Ökonomische Gesichtspunkte

- FDE sind normalerweise bei nahezu allen Landwirten bereits vorhanden, daher werden die Kosten für die FDEs nicht in die Kostenrechnung mit einbezogen, wodurch die auf die Lebensdauer bezogenen Systemkosten sinken und sich die Amortisationszeit verkürzt.
- Auch die PV-Module werden nicht in die Kostenrechnung mit einbezogen, weil die Module von anderen, gescheiterten Projekten übernommen wurden.
- Die gesamten Lebensdauerbezogenen Kosten betragen 7,841.05 €
- Die gesamte aus dem System nutzbar gemachte elektrische Energie beträgt 20.984 kWh.
- Die Energiekosten betragen 0,48 €/kWh.

3. Abschätzung der Umwelteinflüsse

- Die täglichen Laufzeiten der Dieselmotoren wurden von 1-2 Stunden auf ca. 30-50 Minuten verringert, was entsprechend die Treibstoffkosten reduzierte.
- Die Lärmbelästigung wurde entsprechend den Laufzeiten verringert.

Die Ergebnisse der Evaluation und der Analyse der genannten technischen Leistungsfähigkeit, sowie der ökonomischen und ökologischen Beurteilung zeigen, dass das „PB-Bio FDE for HSHS“ eine sehr zufriedenstellende Hybridsystem-Lösung für Landwirte darstellt, wie folgende Zusammenstellung zeigt:

- Das System funktioniert gut und ist leistungsfähig
- Das System ist stabiler und zuverlässiger als SHS
- Flexibles System-Design zur problemlosen Integration in die Kultur und die Lebensumgebung thailändischer Landwirte
- Landwirte als Hauptnutzer können das System mit geringem Investitionsaufwand nutzen, weil meist bereits existierende Komponenten genutzt werden, wie z.B. PV-Module von SHS, Dieselmotoren und Generatoren
- Dieses Hybridsystem kann den wachsenden Bedarf an elektrischer Energie der Landwirte decken, die auch Interesse an komfortsteigernden elektrischen Geräten haben

- Das System kann manuell betrieben werden, ist nicht zu komplex und kann leicht von den Landwirten selbst gewartet werden
- Die Nutzung von Dieselgeneratoren zur Elektrizitätserzeugung ist den Nutzern in der Regel vertraut
- Reduktion der Treibstoffkosten und der Lärmbelästigung im Vergleich zur Elektrizitätserzeugung allein basierend auf Dieselgeneratoren

Der Schlüssel zum Erfolg des Projektes ist die Nähe des „PV-Bio FDE for HSHS“ zu der ursprünglich gewachsenen Struktur der Energieversorgung landwirtschaftlicher Gegenden, in denen eine kleine Anzahl von Häusern zentral von einem Haus aus mit Elektrizität versorgt werden.

Acknowledgements

First of all, I would like to express my sincere gratitude to a number of persons at the Department of Efficient Energy Conversion (IEE-RE) associated with the University of Kassel for their invaluable assistance during the course of my work. I would particularly like to thank my supervisor, Prof. Dr. -Ing. Jürgen Schmid for his valuable assistance throughout the course of this work. I will surely miss the very friendly environment in our IEE-RE department. Full appreciation also goes to Prof. Dr.-Ing. habil. Ingo Stadler who agreed to be my second supervisor. My very special thanks go to Ms Claudia Erdt who assisted me on many occasions.

Secondly, I would like to sincerely thank the members of the School of Renewable Energy Technology (SERT) especially Prof. Dr. Wattanapong for supporting me to provide system components & hardwares in this work, and his helpful visions, discussions and motivations which contributed a lot to the success of this work. My appreciation also goes to following persons: Mr. Konglit Mansiri for his help on various aspects of on all information support through the project, site installation duties, Mr. Chart Chaisit for local activities support on the thesis, Dr. – Ing. Boonyang Plangklang and Dr.- Ing. Nipon Ketjoy on their useful suggestions, Dipl.-Ing. Thorsten Bülo for his kind support of German abstract translation, Dipl.-Ing. Phongsuk Ampha for accommodation hosting during my visit at University of Kassel.

Finally, I would like to thank my wife, Jareepaht Srisukpornchai and my parents, for their fully supports and encouragements all the time.

Place, Date of Disputation:

Kassel,13.06.2008

Table of Content

List of Figures

List of Tables

Nomenclature

A_A	=	Area of PV array [m^2]
Ah	=	Ampere-Hour
Ann Fuel Cost	=	Annual Fuel Cost
Ann Recur Fuel Costs	=	Annual Recurring Fuel Costs
C_B	=	Battery Capacity [kWh]
d	=	Discount Rate
DOD	=	Battery Depth of Discharge [%]
E	=	Total of Electricity Energy [kWh] Produced
E_a	=	Electricity Energy Generated by PV array [kWh]
E_{BU}	=	Energy Generated from Secondary Source [kWh]
E_{el}	=	Real Electric Output Energy of the System [kWh]
E_L	=	Electricity Energy Delivered to Load in Practical [kWh]
E_{glob}	=	Global Radiation on Horizontal Surface [kWh/m^2]
E_{pv}	=	Energy Generated by PV Array and Delivered to Load [kWh]
E_{th}	=	Theoretical Output Energy of System [kWh]
$E_{y, load}$	=	Yearly Daily-Average Load Demand [kWh/day]
FE	=	Fuel Escalation Rate
G_{STC}	=	Solar irradiation at PV Standard Testing Condition [kW/m2]
G_t	=	Solar Radiation
GWh	=	Gigawatt-Hour
H_i	=	Solar Energy Impacting to Area of PV array [kWh/m2]
i	=	Excess Inflation Rate
I_B	=	Discharge Current [A]
I_{cell}	=	Photo Current [A]
I_{pv}	=	PV Current [A]
h	=	Hours
I_{bat}	=	Battery Current [A]
I_D	=	Diode Current [A]
I_{gen}	=	AC Machine Output Current [A]
I_{MMP}	=	Current at Maximum Point of PV Module [A]
I_o	=	Dark Current [A]
I_{ph}	=	Photocurrent [A]
I_{SC}	=	Short-Circuit Current [A]

I_{STC}	=	Incident Global Radiation under Standard Testing Condition
Item Cost	=	Non Recurring in Present Costs
I_{use}	=	Load Use Current [A]
I_{10}	=	Rated Battery Current [A]
k	=	Boltzmann's Constant [$8.65 \cdot 10^{-5}$ eV/K]
kWh	=	Kilowatt-Hours
kVA	=	Kilo VA
kWh_{Σ}	=	Stored Kilowatt-Hour
MW	=	Megawatt
N	=	Period of Analysis in Year
N_d	=	Number Days of Battery Autonomy [day]
Non Recurr Costs	=	Non Recurring Costs
P_{MMP}	=	Power Output at Maximum Point of PV Module [W]
P_o	=	Peak Power of PV Array (kWp)
P_{peak}	=	Peak Power of PV Array under STC [kW_p]
PR	=	Performance Ratio [%]
q	=	Magnitude of the Electron Charge [$1.6 \cdot 10^{-19}$ As]
Q	=	Quality Factor of the System
Q_C	=	Amount put in during Charging [Ah]
Q_D	=	Amount of Charge Able to be Recalled from Battery [Ah]
P_{in}	=	Input Solar Radiation [kW]
P_{pv}	=	Power Generated by PV
P_{use}	=	Power Use by Load
P_{gen}	=	Power Generated by Farmer Diesel Engine Coupling with AC
P_{bat}	=	Power Charge/Discharge from Battery
R_{in}	=	Internal Resistor [Ω]
R_{load}	=	Absolute Temperature [K]
R_n	=	Replacement Year
V	=	Applied Voltage [V]
V_{ac}	=	Alternating Voltage [V]
V_B	=	Terminal Voltage [V]
V_{bat}	=	Battery Voltage [V]
V_C	=	Average Charging Voltage [V]
V_D	=	Average Discharge Voltage [V]
V_{dc}	=	Direct Voltage [V]
V_E	=	Equilibium Voltage [V]
V_{gen}	=	AC Machine Output Voltage [V]
V_{in}	=	Internal Loss Voltage [V]
V_{MMP}	=	Voltage at Maximum Point of PV Module [V]
V_{oc}	=	Open Circuit Voltage [V]
V_{pv}	=	PV Voltage [V]

V_{use}	=	Load Use Voltage [V]
Wh	=	Watt-Hours
Y_a	=	Array Yield [kWh/kW$_p$]
Y_f	=	Final Yield [hour/day]
Y_r	=	Electricity Energy Generated by PV Array by Peak Power in Theory (kWh/kWp)
η	=	Efficiency of the PV Array [decimal]
η_A	=	PV Array Efficiency
η_I	=	Columbic Efficiency [%]
η_{inv}	=	Inverter Efficiency [%]
η_{PV}	=	Total Efficiency [%]
η_V	=	Voltage Efficiency [%]
η_Σ	=	Overall Efficiency [%]

Glossary of Term

AC	Alternating Current
AC Machine	AC asynchronous Motor driven by Farmer Diesel Engine to generate electricity
ALCC	Total Life Cycle Cost Per Year
CFL	Compact Fluorescent Lamp
CO_2	Carbon Dioxide
Cr	Chromium
DC	Direct Current
DEDE	Department of Alternative Energy Development and Energy Efficiency
DOD	Depth of Discharge
DP	Pesticide Data Program
EGAT	Electricity Generating Authority of Thailand
EMS	Energy Management System
EPPO	Energy Policy and Planning Office
ESB	Enhance Single-Buyer
E-TAC	Farmer Diesel Engine with the power range of 8-12 HP
E-TAN	Farmer Diesel Engine with the power range of 12-25 HP
FDE	Farmer Diesel Engine
Fe	Iron
FF	Fill Factor
GDP	Gross Domestic Product
HSHS	Hybrid Solar Home System
IPP	Independent Power Producer
LCC	Life Cycle Cost
MEA	Metropolitan Electricity Authority
MEG	Medium Economic Growth
MPP	Maximum Power Point
Na	Sodium
Ni	Nickel
NESDB	National Economic and Social Board
NO_x	Nitrogen Oxide
O&M	Operation and Maintenance
P	Electric Power
PDP	Power Development Plan of Thailand
PDR Laos	People Democracy Republic of Laos
PEA	Provincial Electricity Authority
PV	Photovoltaic
Rai	Area Unit, 1 Rai is equal 1,600 square meters
REPP	Renewable Energy Power Plant
RPS	Renewable Portfolio Standard
S	Sulphur
SB	Single Buyer

SERT	School of Renewable Energy Technology
SO_2	Sulphur Dioxide
SOC	State of Charge
SPP	Small Power Producer
SHS	Solar Home System
VAT	Value Added Tax

Chapter 1 : Introduction

1.1 Motivations

First stage of this thesis is to review what the current situation. At present, most of Thai populations in rural area approximately 60%– 70% are farmers. Nowadays, agricultural machines so called “Farmer Diesel Engine (FDE)” with power range of 8-12 HP (5.96 – 8.95 kW) are widely used for many purposes like 1 farming activities, 2 water pumping, 3 transportation and 4 generating electricity.

The function of FDE is acted as diesel engine. In daytime farmers usually connect to agricultural car (carriage) for farming or connect to the pump for water pumping. During the night where there is no grid utility supply, farmer simply coupling this FDE with AC Machine to produce electricity in household use.

Currently, the Department of Alternative Energy Development and Energy Efficiency (DEDE) under Thai government is promoting the project of 300,000, 120 W Solar Home Systems (SHS) that owned by Provincial Electricity Authority (PEA) to households in rural area. The problems after SHS project implementation are incurred in the following:

1. People life has been changed. After they have electricity supply, they need to have more appliances e.g. rice cooker, refrigerator for support this comfort life. Those cause increasing of load demand. SHS 120 W will not able to supply farmer electricity need anymore.
2. SHS is PV system that based on only availability of energy source from sun. Even SHS can be back up with battery storage, it is still recognized as unsustainable system, when rainy and cloudy, also when the peak load demand is incurred.

As the problems mentioned above, the project SHS is going to fail as the same to previous PV battery charging project.

In this work, it is recommended to make use of PV resources from failed projects of installed PV-Systems e.g. PV-battery charging station and SHS above and integrate to reliable back up with appropriate renewable source for electrification in non grid utility supply in rural area. The FDE could be an answer for this work because it is existing equipment in farmer hand, fit to their working culture and also farmers have got familiar to operate it.

The most important motivation is the culture. The living culture of Thai farmer families is the cluster community. Each cluster consists of 3-5 households. There is one *“parent house”* will be the single provider who coupling FDE with AC Machine by pulley welt-drive system to provide electricity supply to 2-4 *“child house”*. PV-Bio FDE for HSHS is the system aligns to farmer culture that single parent provider supply electricity to child family houses in his cluster.

The innovative concept of this work will provide the new electrification solution for non-electrified Thai farmer families in rural area. Align to today hybrid system, parallel hybrid configuration system is chosen as model for developing to be “PV-Bio diesel from Farmer Diesel Engine for Hybrid Solar Home System”.

1.2 PV-Bio Diesel from a Farmer Diesel Engine for Hybrid Solar Home Systems (PV-Bio FDE for HSHS Project)

Innovative concept of PV-Bio FDE for HSHS is the integration of existing renewable sources and local technologies for rural power generation supplying to farmer families. This PV-Bio FDE for HSHS consists of main components in the following:

- PV Array: 8 sets of PV-modules 53 W, 2 strings in parallel, each string are 4 modules in series in totally power of 424 W.
- Battery Bank: 4 units of batteries 12 V, 85 Ah in parallel.
- Bi-directional inverter with power rate 1.5 kVA, 48 V_{dc}, 220 V_{ac} 50 Hz
- Charge Controller.
- AC Machine with power rate of 3 kW.
- Farmer Diesel Engine 11 HP (8.2 kW).

The system is the adaptation of parallel hybrid configuration concepts running in 2 modes operation. Mode1: Daytime Operation; PV generators are generating electricity when solar radiation is available in the daytime, while the power exceeds load demand is charged into the batteries controlling by controller. Mode 2: Nighttime Operation; FDE after farming in daytime is utilized in hybrid system by directly coupling to AC Machine to produce electricity supplying peak load demand in the nighttime. The exceed power from AC Machine is regularly recharged into battery for later use.

The chosen site to be installed the system is one cluster of farmer families consisting of 3 households close together in Phichit, province located 60 kilometers in southern from Phitsanulok.

1.3 Research Objectives

The objectives of this thesis are in the following:

- To develop the most appropriate hybrid system by combining existing renewable sources and local technologies.
- To optimize the efficient use of FDE to generate electricity.
- To design the prototype of PV-Bio diesel from Farmer Diesel Engine for Hybrid Solar Home System for rural electricity generation for non-electrified Thai farmer families.
- To implement the design prototype at selected demo-site.
- To track monitored data and undertake the performance analysis of the system, also economical, social and environmental benefits assessment.

1.4 Work Structure

The thesis is structured as follow:

Chapter 2 will present Thailand electricity outlook. The overview of electricity supply industry, current electricity demand and supply in Thailand, development directions of Thailand's electricity sector and road ahead to renewable will be discussed in this chapter.

Chapter 3 will review 3 basic configurations of PV-Diesel hybrid system. Its operation and basic system components are mentioned and ended up with rule of thumb methods which are most used as practical guidelines to design and size each component of PV-Diesel hybrid systems.

Chapter 4 will present innovative design concept of PV-Bio diesel from Farmer Diesel Engine for Hybrid Solar Home System. Its inspiration components and mode operational principle will be described in this chapter.

Chapter 5 will present the implementation, data measuring and technical performance analysis of this system.

Chapter 6 will present the project analysis in term of economic using Life Cycle Costs (LCC) methods. The social and environmental benefits will be also evaluated in this chapter.

Chapter 7 will conclude this work.

Chapter 2 : Thailand Electricity Outlook

2.1 Overview of Electricity Supply Industry

Thailand's electricity industry is a hybrid structure as can be seen in Figure 2-1 that is in the process of evolution. Currently, the electricity industry structure is similar to many others in the world. The Electricity Generating Authority of Thailand (EGAT) operates most of the generating system and transmission systems in Thailand. Even though, the government has opened access for the private sector to participate in the generation business in the form of Small Power Producers (SPPs) and Independent Power Producers (IPPs), generated electricity from both SPPs and IPPs have to firstly sell to EGAT. Then EGAT will further trade the electricity to through the Metropolitan Electricity Authority (MEA) and the Provincial Electricity Authority (PEA) to the End Users. MEA is responsible for supplying electricity to consumers in Bangkok, Nonthaburi and Samut Prakarn provinces while PEA is responsible for supplying electricity to the remaining provinces of the country. By the electricity market structure, almost all consumers nationwide depend only on the services of MEA and PEA, without other options since there is no competition in the service provision and distribution of electricity. Exceptions exist for industrial customers whose facilities are located near an SPP project, and hence options are available for them whether to have the SPP or PEA/MEA as their power suppliers.

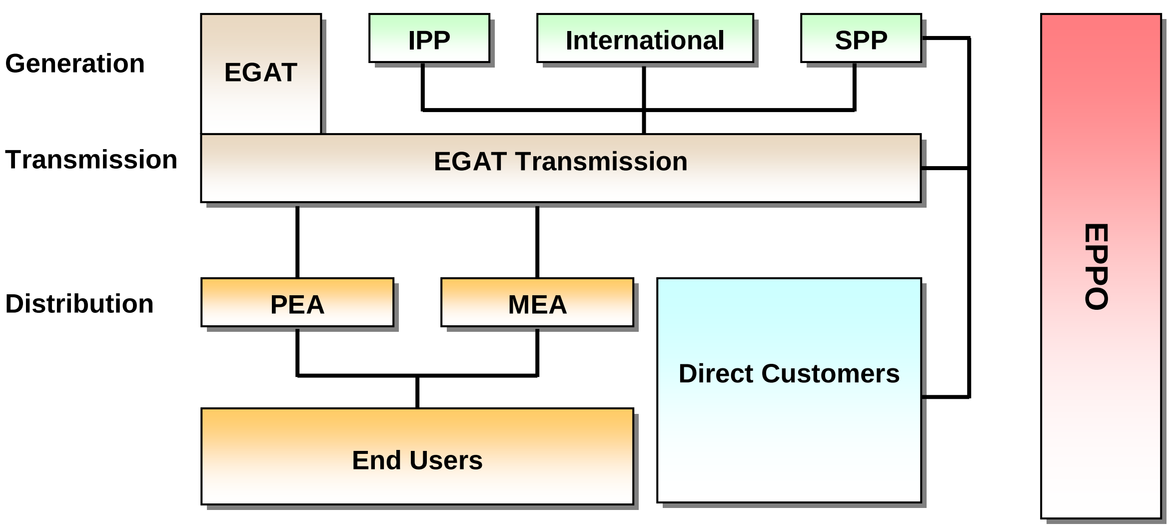

Figure 2-1: Existing Electricity Market Structure [1]

Figure 2-2 illustrates the proposed new structure entitled "enhance single buyer" (ESB, a variation on the single buyer model).

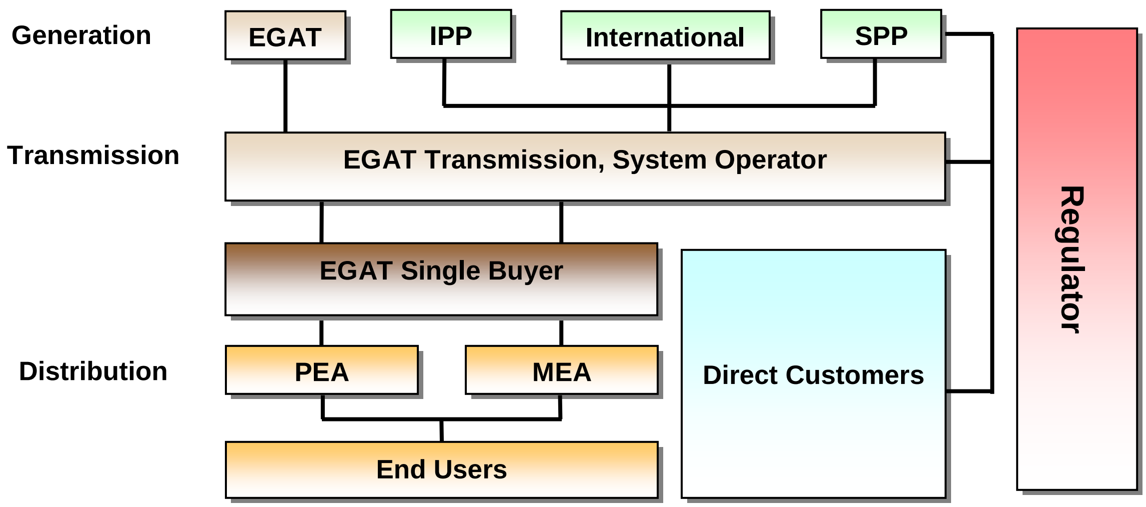

Figure 2-2: Proposed Electricity Market Structure- Enhanced Single [1]

The proposed ESB structure has regulation in the following [1]

Account unbundling of EGAT's business units (generation and transmission).
EGAT to retain generation. New capacity to be allocated through competitive bidding process overseen by regulator.
EGAT retains transmission with regulated tariffs. Transmission responsible for network operations and maintenance. Transmission regulated via the Grid Code and transmission license. Third party access to be reviewed at later point.
System operator to be ring-fenced within EGAT. System operator retains obligation for dispatch planning, dispatch real time balancing and network operations planning.
Single Buyer (SB) to be transparent within transmission. SB will be responsible for contracting adequate capacity and accountable for long term system adequacy planning.
MEA and PEA will continue to operate their networks with regulated tariffs; MEA and PEA regulated via the Grid Code and distribution license. Third party access to be reviewed at later point.
End user tariffs will continue to be regulated by the regulator, large customer contestability to be reviewed in the future.
Regulator to enforce the Grid Code and generation, transmission, distribution licenses. Regulator to coordinate long term system adequacy planning and manage new PPA award process.

2.2 Electricity Demand and Supply in Thailand

The economic growth in Thailand is definitely one of the important driven forces for the large growth of electricity consumption. Since the mid of 1980s Thailand has had one of the most rapidly growing economics in the Asia Pacific region, with growth rates in Gross Domestic Product (GDP) nearing 10%. Over the same period Thailand has also dramatically increased its electricity demand at high rate averaged over 13 %. Economic growth slowed to turn down in 1998 and growth in electricity consumption has been zero between1997 and 1998. The decline of the Thai economy is an effect of the Asian financial crisis resulted in a downward in domestic demand for electricity, before rebounding in 1999.

After economic crisis recovery in 1999, both GDP and electricity demand have been growing by moderate rate which are around 5% and 7% respectively.

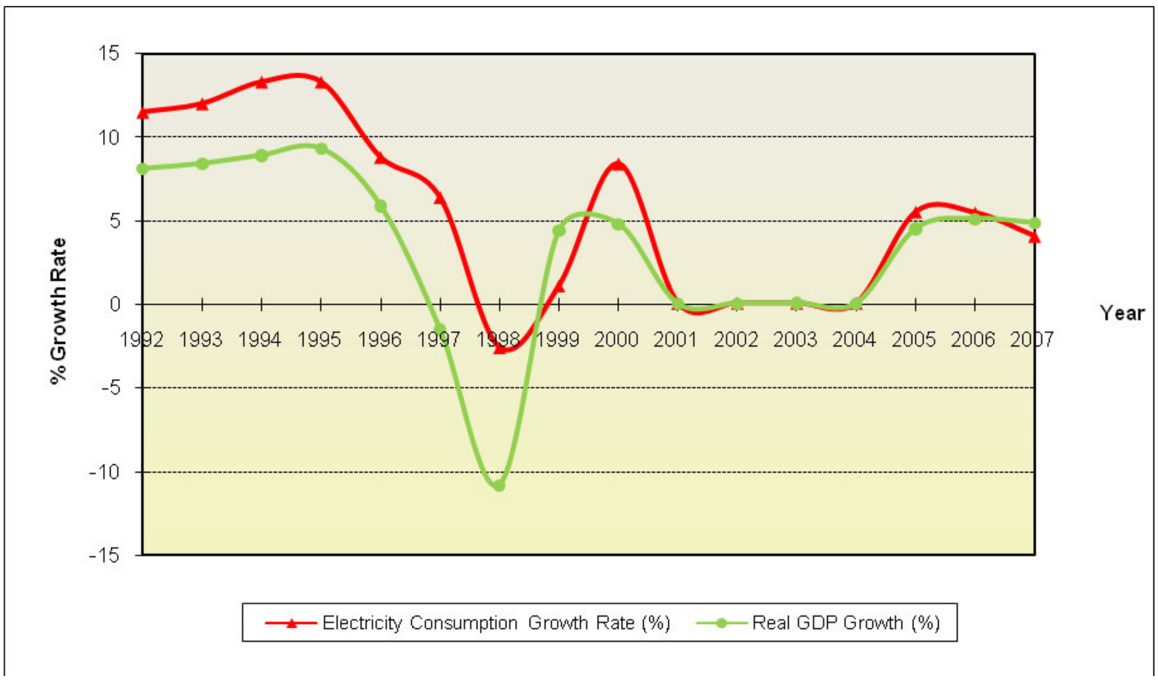

Figure 2-3: Correlation between GDP and Electricity Consumption [2, 3, 24]

In 2004, the total electricity consumption was 113,979 GWh which increase about 7.39% from the previous year. The demand by industry constitutes the biggest portion of electricity consumption, sharing about 44.41% of total demand, accounted for 50,618 GWh. Table2-1 highlights electricity consumption by various economic sectors for the whole country in 2003 to most up to date 2007, it represent regularly growth of electricity consumption in every year.

Table 2-1: Electricity Consumption by Various Economic Sectors [3]

Electricity Consumption (GWH)	2003	2004	2005	2006	2007
Residential	23,315	24,538	25,514	26,915	28,145
Business	25,350	28,563	30,164	31,702	32,885
Industrial	48,252	50,618	53,894	56,995	59,472
Agricultural	228	245	249.52	240	272.00
Others	7,043	7,887	8,406.63	8,898	9,292.17
EGAT Direct Customer	1,949	2,128	2,409.19	2,453	2,675.80
Total	106,137	113,979	120,637	127,237	132,741

As of June 2005, the peak electricity demand set on April 26, 2005 March was 20537.5 MW, which increased 1,211.70 MW or 6.3 % from the previous year is in Figure 2-4.

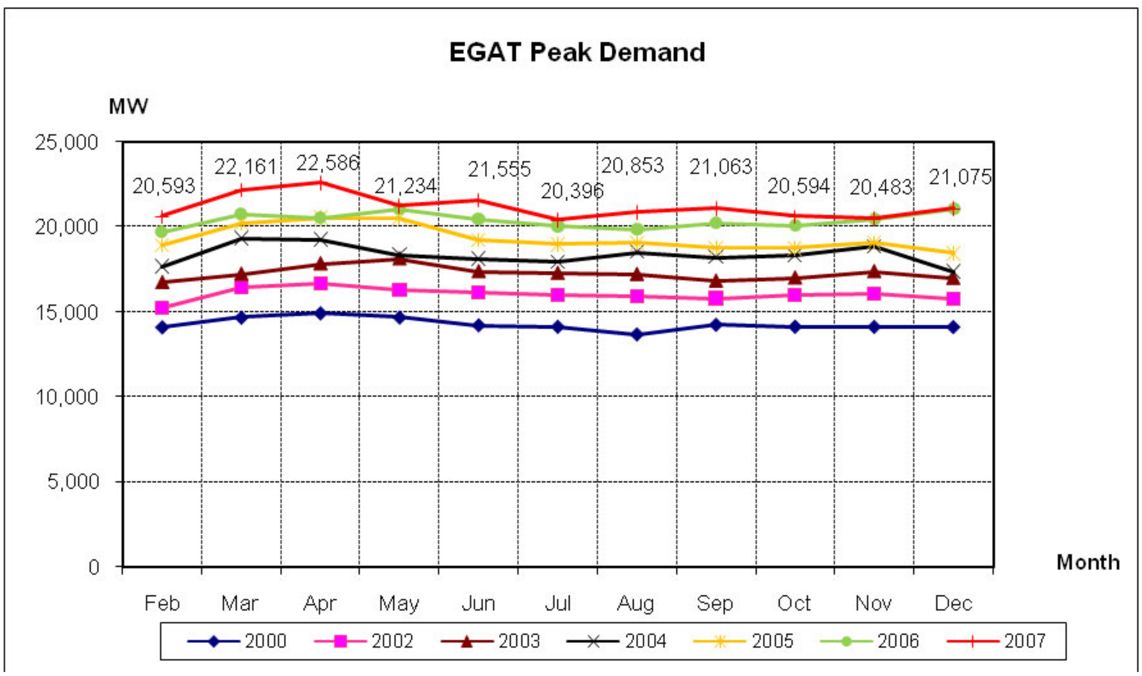

Figure 2-4: EGAT Peak Demand

While the total installed capacity of the power plant by fuel type as of November, 2007 was 135,159 GWH, which was over 1.29 times larger than peak demand. This installed capacity major portion is relied on IPP at 42.30%, the second rank is Natural gas Power Plant at 25.12%. The power plant could be classified by type as shown in Table 2-2.

Table 2-2: Power Generation by Type of Fuel (as of November 2007) [3]

Type of systems	Installed Capacity (GWH)	% Sharing
Hydro Power Plant	7,200.18	5.33%
Fuel Oil Power Plant	2,513.79	1.86%
Lignite Power Plant	16,981.23	12.56%
Natural Gas Power Plant	33,957.55	25.12%
Diesel Power Plant	25.00	0.02%
Geothermal Power Plant	1.66	0.00%
Non conventional Power Plant	0.73	0.00%
Imported	4,069.99	3.01%
DEDP	20.72	0.02%
SPP	13,220.55	9.78%
IPP	57,167.61	42.30%
Total	135,159.01	100.00%

2.3 Source of Power Generation [3]

Electricity generation has been utilized base on varieties source of fuel. The proportion of source of power generation in 2007 is shown in Figure 2-5.

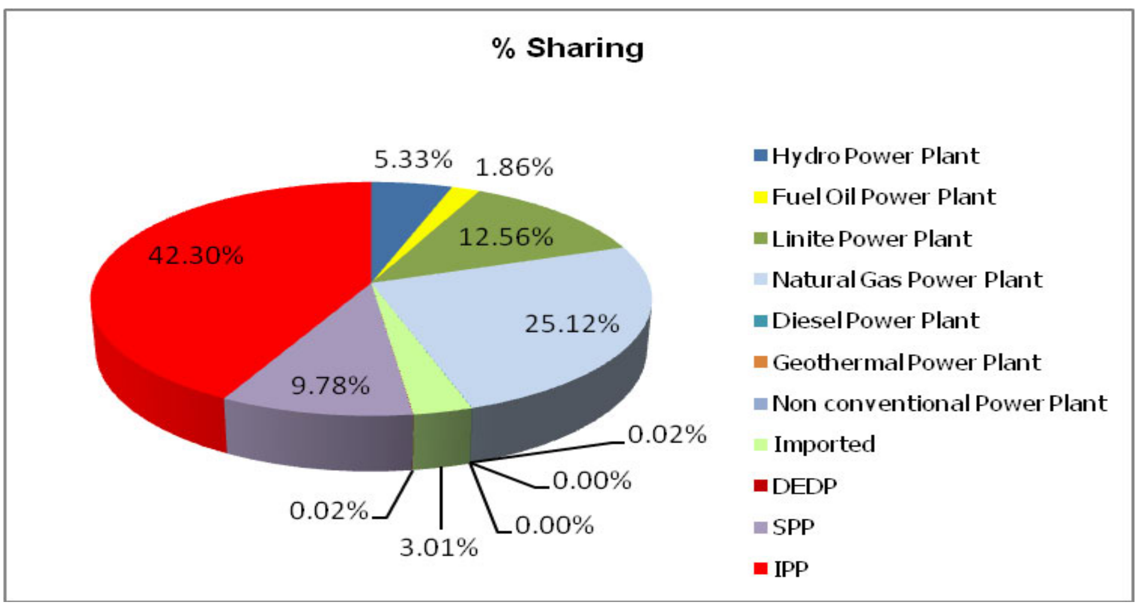

Figure 2-5: Source of Power Generation in 2004 (by Fuel Type) [3]

In 1980, two thirds of power generation used fuel oil as its source. At that time, there was no use of natural gas for electricity generation. In an effort to achieve lowest possible production costs, electricity generation in Thailand tried to minimize its oil base generation due to the rising oil prices while natural gas and coal began to use substantially as source of generation.

Since 1990, production and consumption of natural gas in Thailand greatly increased, despite the recession. Part of this rising up is due to the switchover to natural gas from other fuels for electricity generation. Presently, about 70 % of the electricity generated in Thailand is based on natural gas.The only coal presently being mined in Thailand is lignite, which is used exclusively for power production. In 2004, domestically mined lignite is the fuel for 14% of Thailand's electric power production. Thailand also imports higher quality bituminous coal for industrial uses. About 1.7% of electricity generation was from imported coal.

Thailand has considerable hydroelectric power resources, with six existing power plants of greater than 100 MWe of capacity. About 6.5% of the electricity generation comes from hydropower plants. Renewable power generation share is currently about 0.7% of total electricity generation.

2.4 Development Directions of Thailand’s Electricity Sector

Since the power demand has the tendency to grow in step with the national economy. Base on the economic situation data with Medium Economic Growth (MEG) at 6.5% using for Thailand load forecast rate, increasing rate of electricity capacity expected to 7.5% during the year 2004-2008; 6.8% during 2009-2013 and 6.4% during 2014-2015. As a result total generating capacity will be increase to 40,978 MW. According to this load forecast, power demand is expected to reach 193,530 GWh in 2010 and 265,788 GWh in 2016 as shown in Figure 2-6.

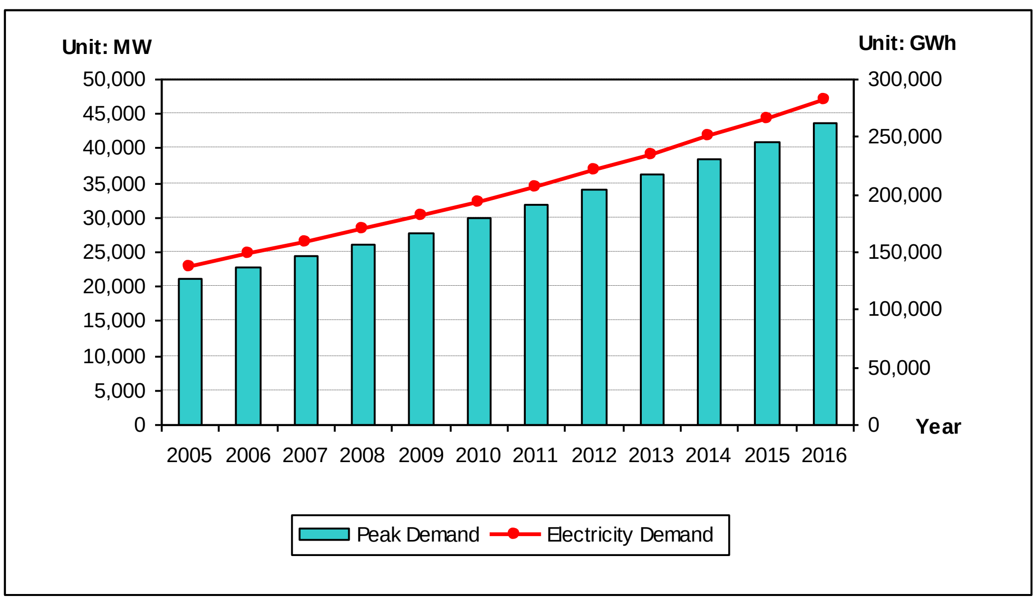

Figure 2-6: EGAT’s Peak Demand and Electricity Demand Forecast [3]

To increase the efficiency and to maximize power generation as well as to reduce the investment on the construction of new power plant, government has the peak cut policy by using diesel engines installed at the large industries and business as their emergency standby to run during the high peak demand about 500 MW from the year 2006 onwards.

Regarding Power Development Plan of Thailand (PDP) in year 2004 covering from 2004 to 2015, source of power supply is advised to locate close to the power demand source to increase the reliability and to reduce the loss in the system. To develop power supply system by region, the Southern and the Northeastern regions have been prioritizes to consider because these regions have inadequate power plants to supply to the regional require due to the difficulties with regard to fuels. Therefore the power capacity and energy from other regions and neighboring countries such as Malaysia and PDR Laos have to be transferred to these regions.

The share of natural gas is expected to decrease, while imported coal is forecasted to increase as well as renewable source during 2010 to 2015. However, natural gas is still dominant energy source in electricity generation mix, with its share about 66.3%, 75.1% and 49.4 % in year 2005, 2010, and 2015 respectively as presented in Figure 2-7.

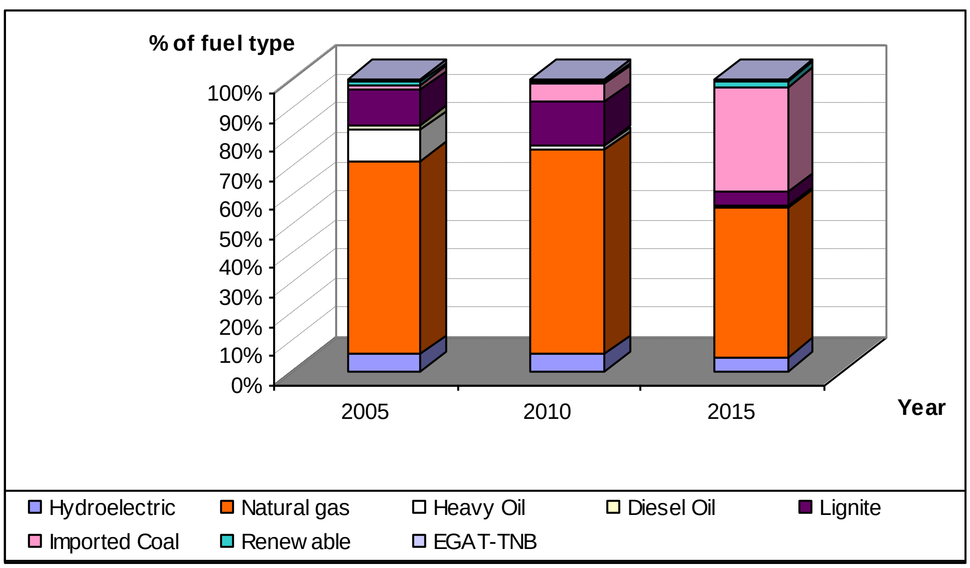

Figure 2-7: Electricity Generating Capacity Forecast (by Fuel Type)

2.5 Road Ahead to Renewable Energy

Thailand also has Renewable Portfolio Standard (RPS) Policy at the proportion of not less than 5% of the new generating capacity which used fossil fuels. To be in line with such policy, PDP 2004 Plan is therefore incorporated RPS power plant during 2011-2014 about 630 MW. Apply the policy on the use of the renewable energy into the system not less than 5% of the newly built power plants beginning from 2011 onwards. The renewable portfolio system project is the project that uses non conventional sources such as biomass, wind energy, solar energy, and hydro energy as the fuel.

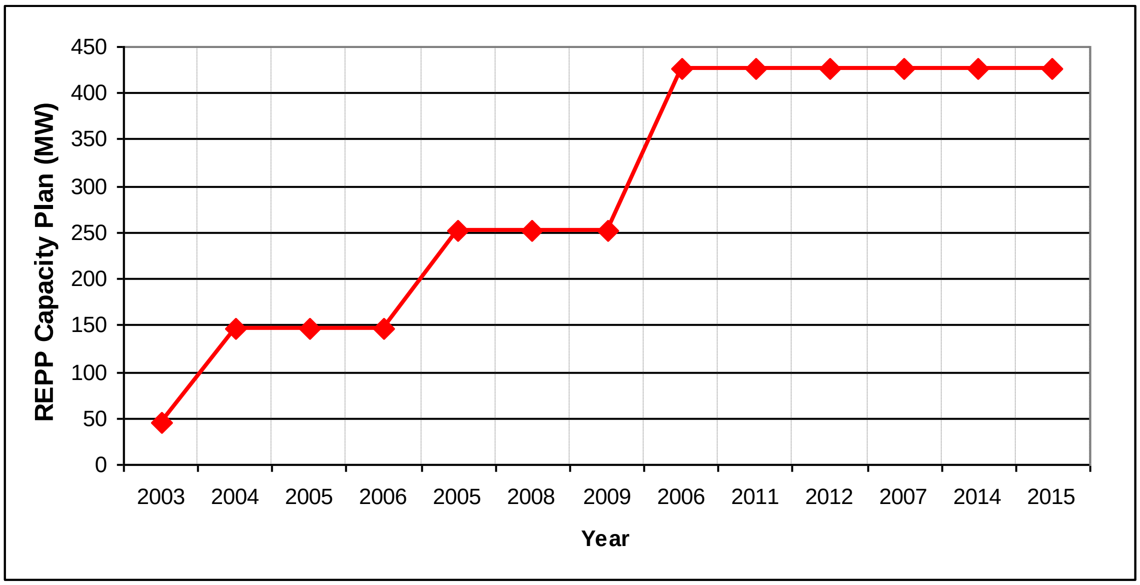

Figure 2-8: Future Capacity Plan of Renewable Energy Power Plant. [1]

Figure 2-8 represents future capacity plan of Renewable Energy Power Plant (REPP). Align to RPS policy, during 2003 – 2010; the capacity plan of newly installed renewable power plant is step increasing to meet 5% of new power plants in 2011.

Plan Establishing after power development plan 2007 (PDP 2007) was updated in the following:

1. The candidate power plants considered are
   - Thermal power plant (coal-fired) of 700 MW each,
   - Combined cycle power plant (LNG) of 700 MW each,
   - Gas turbine power plant (diesel) of 230 MW each,
   - Thermal power plant (nuclear) of 1,000 MW each.
   - Coal-fired power plants could be online in 2014 as the earliest.
   - Nuclear power plants could be online in 2020 as the earliest,

2. Power purchases from neighboring countries to supplement domestic generation,

3. Cancellation of the renewable portfolio standard (RPS) policy from 2011 onwards, to be replaced with the renewable energy promotion by the government in the SPPs and VSPPs programs. The amount of power purchased from firm SPPs, increased to 4,000 MW from the retained 2,300 MW at present, minimum reserve margin retained at 15%, and loss of load probability (LOLP) not to exceed 24 hours a year,

4. Consideration on the supply side management with regards to the technology of combined heat and power (CHP) to improve the efficiency of the EGAT power plants,

5. Cancellation of the Peak Cut program, due to the increase in diesel oil price, as well as the decline of power demand resulting in adequate reserve margin.

Chapter 3 : Models of PV Diesel Hybrid Technologies

3.1 PV Diesel Hybrid System Configurations & Operations

PV Diesel Hybrid energy systems generate AC electricity by combining photovoltaic array with inverter to operate alternately or in parallel with conventional diesel engine generator and back up battery bank. By reviewing typical PV Diesel Hybrid system, the most common system configurations can be classified in the following:

- Series hybrid energy systems
- Switched hybrid energy systems
- Parallel hybrid energy systems

3.1.1 Series Hybrid Configuration

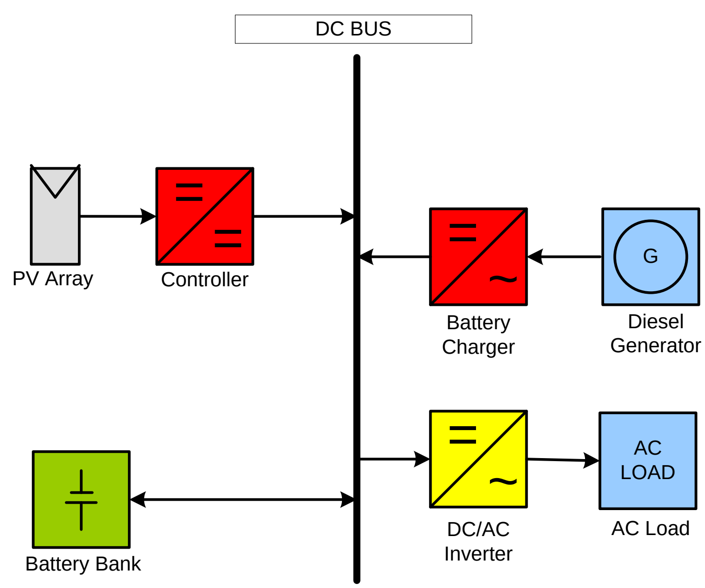

Figure 3-1: Series Configuration

The Series hybrid configuration or DC-BUS system is shown in Figure 3-1, the AC power generate by diesel generator is first rectified to DC power and then again converted back to AC by DC/AC inverter before supplying to AC load. This working condition incurs significant conversion losses. During low electricity demand, the diesel generator is regularly on the switch off stage and the load can be supplied by PV together with store energy from battery. Depending on the power supplied by the PV array and the diesel generator as well as the load demand, the battery bank is either charged or discharged. The controller prevents overcharging of the battery bank from the PV generator when the PV power exceeds the load demand and the batteries are fully charged. The capacity of battery bank and inverter should meet the peak load demand. The capacity of diesel generator should also meet the peak load and charging the battery bank simultaneously.

3.1.2 Switched Hybrid Configuration

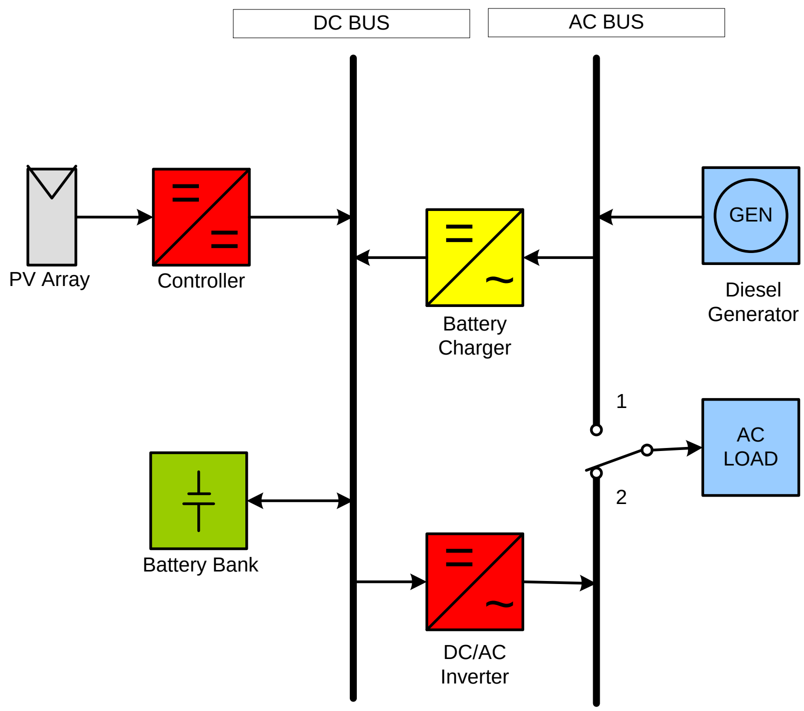

Figure 3-2: Switch Configuration

The switched hybrid system or AC-DC Bus system is shown in Figure 3-2. The operation allows battery bank to be charged by the diesel generator and the PV array. The load can be supplied directly by the diesel generator as the AC source, which results in a higher overall conversion efficiency comparing to the series configuration. Typically the diesel generator output-power will exceed the load demand; excess energy will be used to recharge the battery bank. During period of low electricity demand, the diesel generator is switched off and the load is supplied by the PV array, together with stored energy from the battery bank.

Switched hybrid system can operated either in manual mode or automatic mode up to system design criteria.

3.1.3 Parallel Hybrid Configuration

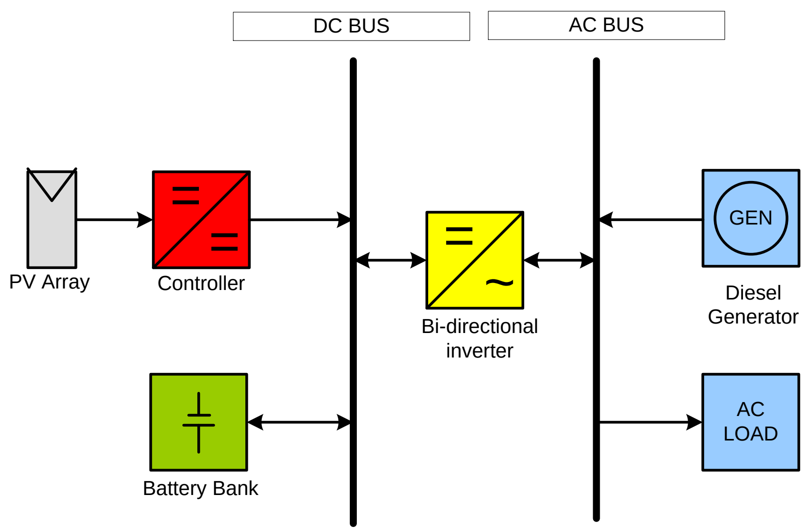

Figure 3-3: Parallel Configuration

The Parallel configuration or AC Bus system as shown in Figure 3-3 allows all energy sources to supply the load separately at low, medium or peak load demand by combining by synchronizing the inverter with the AC output. The diesel generator can supply the load directly. The bi-directional inverter can charge the battery bank (rectifier operation) when excess energy is available from diesel generator, in the same time act as a DC-AC converter (inverter operation). During low energy demand, excess energy from PV array is used to charge the battery bank.

The Parallel hybrid system collects two significant improvements over the series and switched hybrid system. Firstly, the capacity is from inverter plus the diesel generator capacity, rather than individual component ratings that limits the maximum load. Secondly, the capability to synchronize the inverter with the diesel generator allows greater flexibility to optimize the operation of the system.

3.2 Basic Components of PV Diesel Hybrid System

This section will give the overview of basic components of PV Diesel Hybrid System. The main focused components will be discussed in the following:

- Photovoltaic Modules (PV-Modules)
- Energy Storage – Battery Bank
- Diesel Generator
- Charge Controller
- Inverter

3.2.1 Photovoltaic Modules (PV-Modules) [5]

The PV cell operation is based on the ability of semiconductors to converts sunlight directly into DC electricity by exploiting the *photovoltaic effect*. The PV cell is made from p-n junction semiconductors, which has principle operation in common with other solid-state electronic devices, such as diode. For practical operation, solar cells are usually assembled into modules.

The I-V Characteristics of a diode is given by Shockley equation

$$I_D = I_0 \cdot \left[exp\left(\frac{qV}{kT}\right) - 1 \right] \qquad (3\text{-}1)$$

where:

I_D	=	diode current [A]
I_O	=	dark current [A]
q	=	magnitude of the electron charge [$1.6 \cdot 10^{-19}$ As]
V	=	applied voltage [V]: plus = forward bias, minus = reverse bias
k	=	Boltzmann's constant [$8.65 \cdot 10^{-5}$ eV/K]
T	=	absolute temperature [K]

Once PV cell is under illumination, free charge carriers are created due to the photovoltaic effect. The photocurrent (I_{ph}) is then internally generated in the solar cell. The *I-V* characteristics of PV cell can be represented by an equivalent circuit diagram in Figure 3-4. It consists of the diode created by the p-n junction and a photocurrent source with current magnitude depending on the radiation intensity. An adjustable resistor is connected to the solar cell as a load.

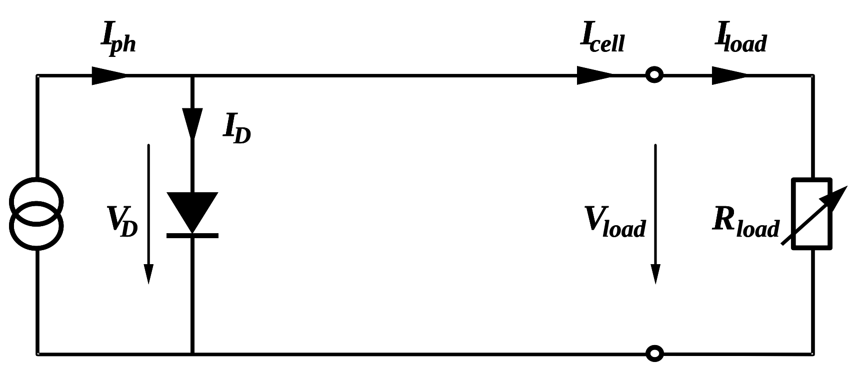

Figure 3-4: Equivalent Circuit Diagram [5]

The mathematical process of an ideal exposed solar cell is the following equation

$$I_{cell} \quad = \quad I_{ph} - I_D = I_{ph} - I_0 \cdot \left(e^{\frac{qV}{kT}} - 1 \right) \qquad (3\text{-}2)$$

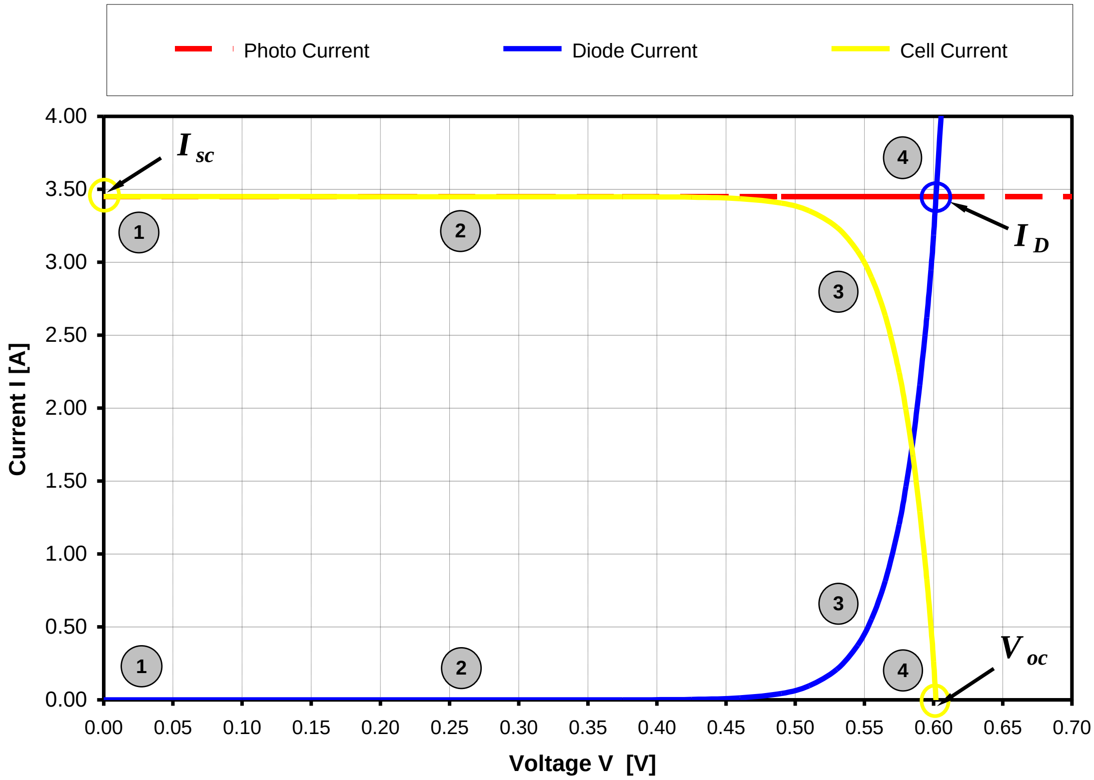

Figure 3-5: Construction of Solar Cell Curve from Diode Curve [5]

Short Circuit Current (I_{sc})

Short circuit is defined when apply R_{load} = 0, thus the cell current has its maximum at this point with the value I_{cell} and refers to the *short-circuit current I_{sc}.*

$$I_{sc} \quad = I_{cell} = I_{ph} \qquad (3\text{-}3)$$

Open Circuit Voltage (V_{oc})

Open circuit is defined when apply $R_{load} = \infty$ the output current is then zero ($I_{cell} = 0$), thus the entire photocurrent flows through the internal. The *open-circuit voltage, V_{oc}* can be given by (3-4).

$$V_{oc} = \frac{kT}{q} \cdot ln\left(\frac{I_{ph}}{I_o} + 1\right) \qquad (3\text{-}4)$$

Power is the product of current and voltage, therefore a curve of the power delivered by a solar cell will be obtained by a given radiation level as shown in Figure 3-6.

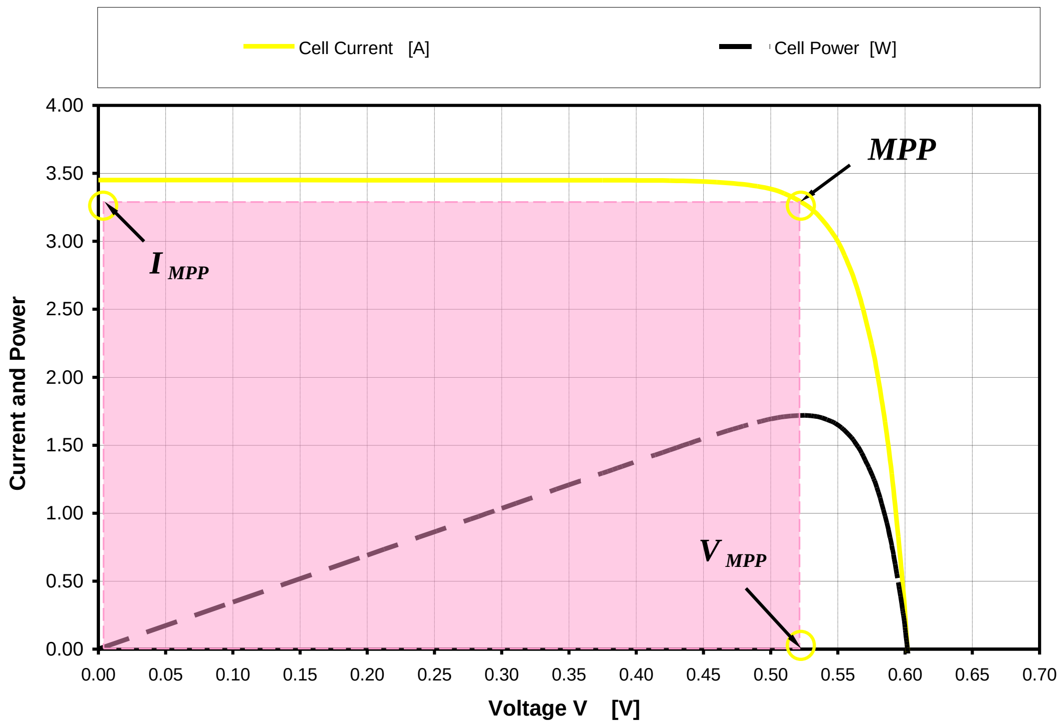

Figure 3-6: Power Curve and Maximum Power Point (MPP) [5]

Maximum Power Point

The "*maximum power point (MPP)"* represents the working point, at which the solar cell can deliver maximum power for a given radiation intensity. It is situated near the bend of the I-V characteristic curve. The corresponding values of V_{MMP} and I_{MMP} can be estimated from V_{oc} and I_{sc} as follows

$$V_{MPP} \approx (0.75 - 0.9)\ V_{oc}$$

$$I_{MPP} \approx (0.85 - 0.95)\ I_{sc}$$

In addition, the quantity

$$FF = \frac{(V_{MPP} \cdot I_{MPP})}{(V_{oc} \cdot I_{sc})} \qquad (3\text{-}5)$$

The *"Fill Factor (FF)"* represents the measure for the quality of the solar cell. It indicates how far the I-V characteristic curve approximates to a rectangle. Normally the value for crystalline solar cells is about 0.7-0.8.
The maximum output power of the cell is then

$$P_{MPP} = V_{MPP} \cdot I_{MPP} = V_{oc} \cdot I_{sc} \cdot FF \qquad (3\text{-}6)$$

Thus, the efficiency of the solar cell (η), which refers to the ratio of the output electrical energy to the input solar radiation (P_{in}), is defined by the following relation.

$$\eta = \frac{V_{oc} \cdot I_{sc} \cdot FF}{P_{in}} \qquad (3\text{-}7)$$

Until now the highest obtained efficiencies of the silicon solar cells with irradiation of a solar spectrum AM 1.5 are approximately 24 %. The efficiencies of the silicon solar cells from the line production are between 10%-14 %. The theoretical efficiency of the silicon solar cell is approximately 26-27 %.

Effect of Irradiation

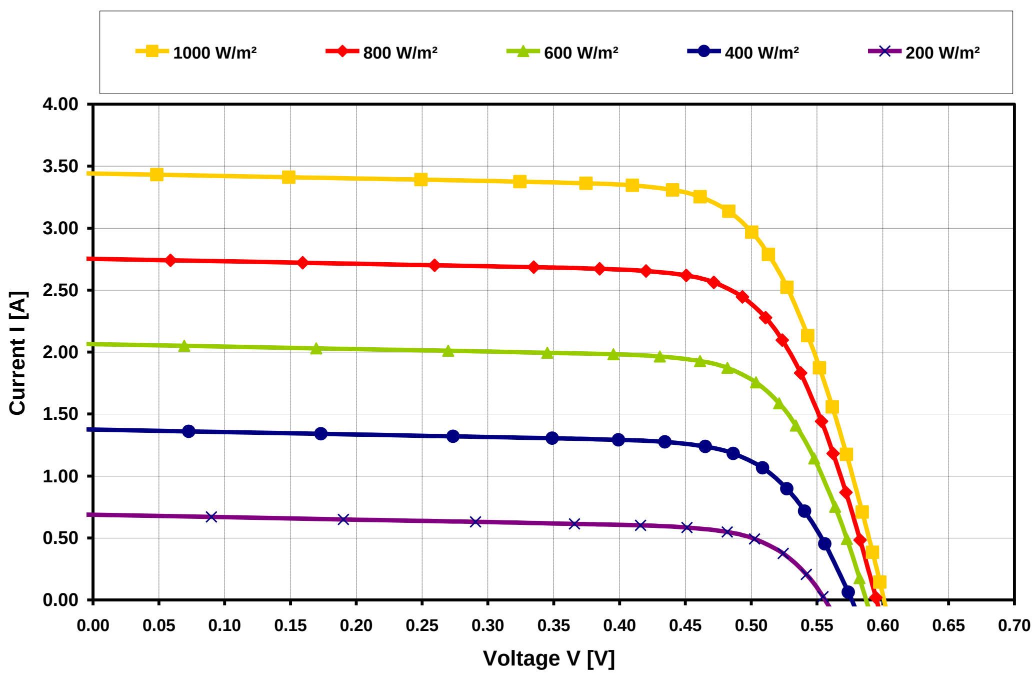

Figure 3-7: I-V Characteristic Curve at Different Irradiation [5]

Effect of Temperature

As a consequence of increasing minority carrier diffusion lengths the photocurrent, the short-circuit current is increasing slightly.

I_{sc} increases by about 0.07 % / K

V_{oc} is strongly temperature-dependent:

V_{oc} sinks by about 0.4 % / K

Since the cell voltage and current depend on the temperature, the supplied electric power (*P*) also varies with the change of temperature:

P sinks by about 0.4 – 0.5 % / K

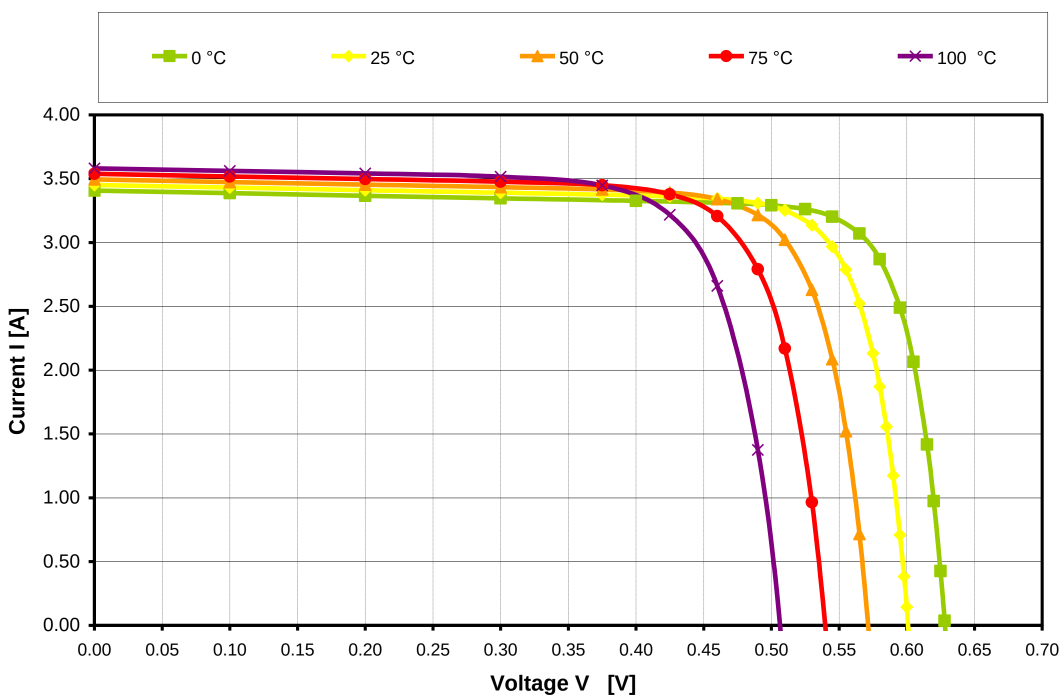

Figure 3-8: Effects of Temperature [5]

Series Connection

In a series connection, the same current flows through each cell whereas the total voltage is the sum of the voltage across each cell.

The I-V characteristic curve of the complete configuration, In Figure 3-9 presents a series connection by adding the single cell voltage values corresponding to each current value point for point. The following characteristic curves result for a given radiation intensity, which is equal for three of solar cells.

Parallel Connection

In a parallel-connected configuration the voltage across each cell is equal whereas the total current is the sum of all the individual cell currents. Accordingly, the current-voltage characteristic curve of the complete configuration is obtained, as shown in Figure 3-10, by adding the single cell current values corresponding to each voltage value point for point.

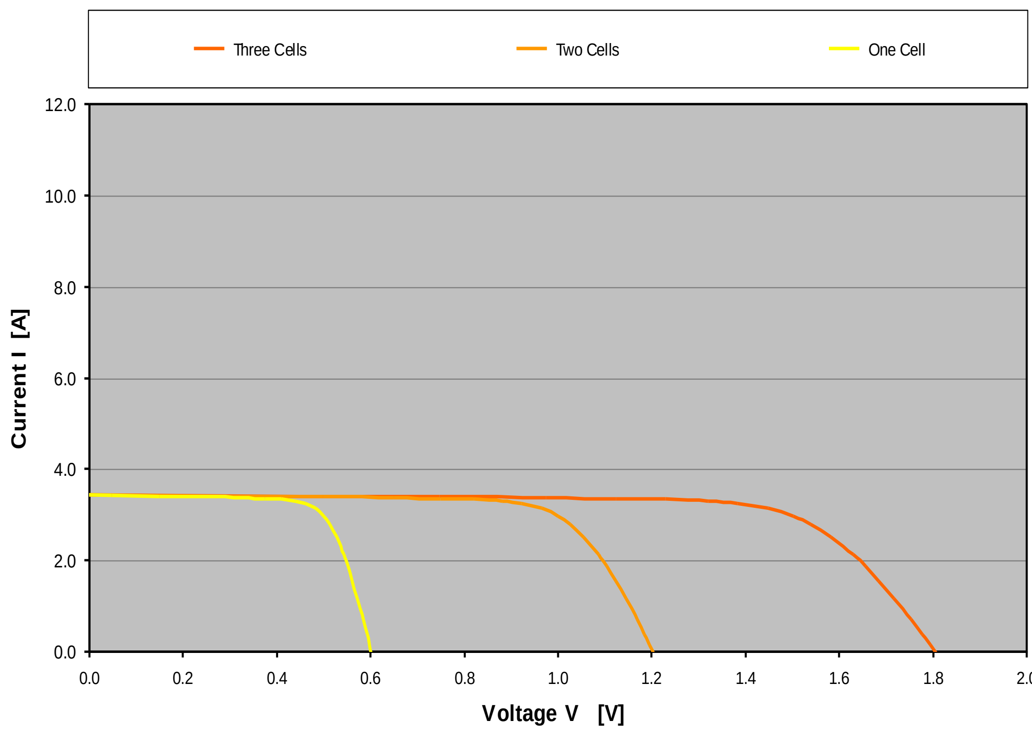

Figure 3-9: I-V Characteristic Curve for Series Connection [5]

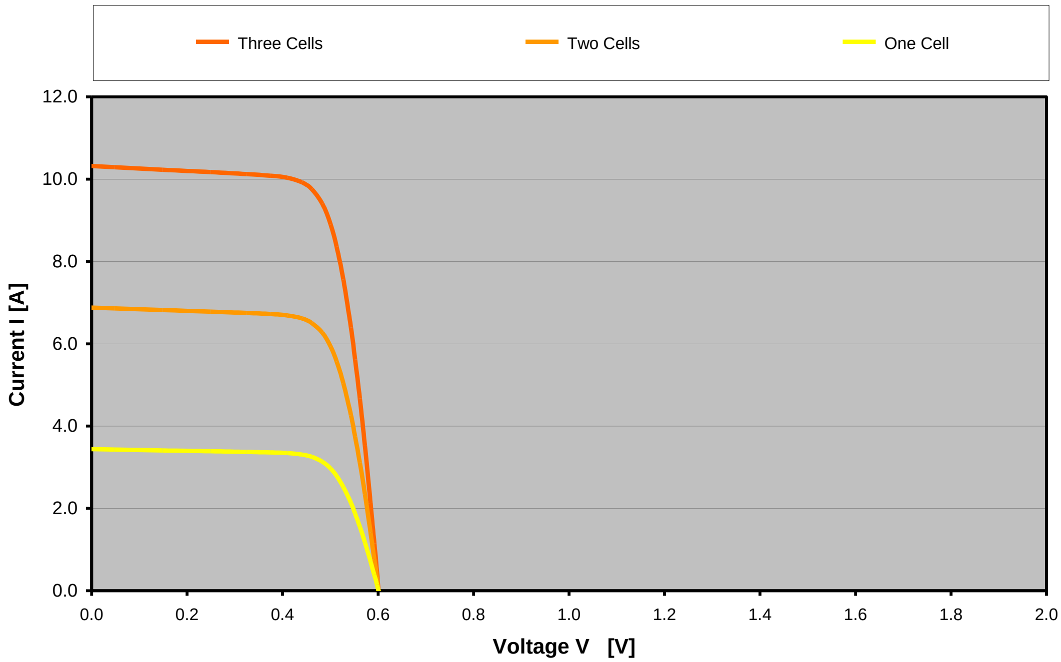

Figure 3-10: I-V Characteristic Curve for Parallel Connection [5]

3.2.2 Energy Storage - Battery Bank [5, 11]

The basic characteristic of solar energy supply is intrinsically variable in time. This causes electricity generating by PV generator to vary accordingly. To guarantee reliable and continual electricity supply to stand-alone PV system, batteries are need for energy storage. Thus, batteries are purposely used to store excess energy for later use. The batteries in most common use in hybrid systems are the deep-cycle lead acid type as Present options cause of availability and cost effectiveness.

There are several other appropriate types such as sodium-sulphur (Na-S), nickel-iron (Ni-Fe) as Medium term options and iron-chromium redex (Fe-Cr redox) as Long term (future) options but those are either too costly or too unreliable in practical application use [11].

General Lead – Acid Batteries Workings [14]

Batteries generally consist of one or more 2V-cells wired in series. Each cell consists of positive and negative plates that are immersed in the electrolyte of mostly sulphuric acid diluted with pure water. On discharging stage, a chemical reaction between two plates and the electrolyte produces electricity. This chemical reaction is reversed when battery is charged.

The thickness of the battery's plates determines the maximum depth of discharge (DOD) beyond which the battery suffer damage. DOD describes how much battery is discharged in a cycle before it is charged again which is the main factor effecting on the lifetime of lead-acid batteries. Swallow cycle batteries, such as car batteries, have thin plates which are designed to produce a large current for short period of time. Those should not be deeper discharged than 10%-20% DOD, then after which the battery is deteriorated easily. Swallow cycle batteries are usually not suited for hybrid systems but are often used anyway in small home systems in developing countries due to the lack of any alternatives. Deep cycle batteries have thick tubular plates and can often be discharged up to 70% - 80%. However, this type of batteries can not be quickly charged or discharged.

Storage Capacity

Generally, the storage capacity of a battery is given in Ampere-hours (Ah) showing how many hours a certain current can be taken from the charged battery until the battery is discharged, i.e. until the battery voltage drops to the discharge voltage threshold.

After multiplying with the batter's nominal voltage, result to the dischargeable energy in Watt-hours (Wh) or kilowatt-hours (kWh).

The value of the storage capacity depends on its operation, age and maintenance. The storage capacity is increased when the battery charging and discharging rates become slow. Most battery manufacturers therefore give the rated capacity of their batteries always with regard to a certain discharge current.

The *r*ated battery capacity refers to the capacity of the battery under given standard conditions: practically is defined at 20 °C by discharging the battery with a *rated battery current* (I_{10}), which refers usually to a constant current, with which the battery will be completely discharged in 10 hours. Some battery manufacturers indicate the 100-hour discharge capacity for batteries intended for PV applications. When comparing such capacity, it should be remembered that, for a given battery, the 100-hour capacity is always at least 30 % higher than the 10-hour capacity [5].

Temperature Effect

Besides, battery capacity is also affected by the temperature: it falls by approximately 1 % per degree below about 20 °C. Moreover, extreme high temperatures accelerate aging, self-discharge and electrolyte usage [5].

Equivalent Circuit

A basic equivalent circuit of the lead-acid battery is modeled by a voltage source with an equilibrium voltage (V_E) in series with an internal resistor (R_{in}) (Fig. 3-11).

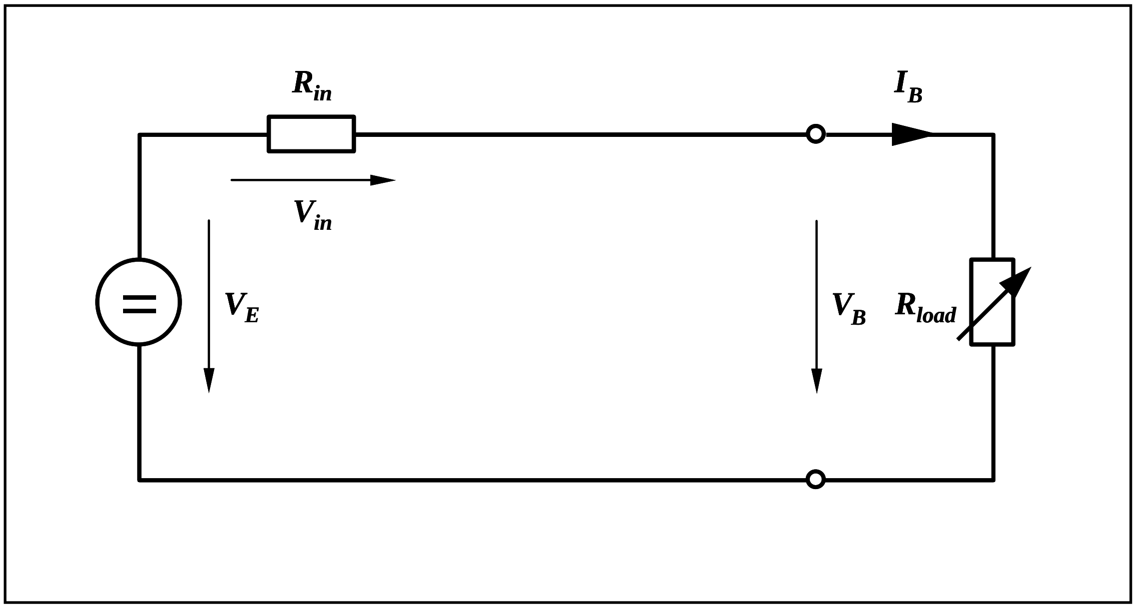

Figure 3-11: Basic Equivalent Circuit of Lead-Acid Battery for Current State [5]

The configuration can describe only a current state because the magnitude of V_E and R_{in} are not actually constant. Those are the function of many parameters such as state of charge (SOC), temperature, current density and aging of the battery. Furthermore, the parameters depend also on the current direction (charging or discharge) [6].

While current is discharging from or charging into a battery, the voltage measured at the battery terminals, so called *"terminal voltage"* (V_B) will be different from the voltage that would be measured at those terminals while the battery were at rest or under open-circuit condition ($V_B = V_E$). When current is drawn from the battery, the voltage will be lower than V_E. When current is flowing into the battery, the terminal voltage will be higher than V_E. For example, at each moment during discharge phase the terminal voltage can be derived as follow:

$$V_B = V_E - V_{in} \tag{3-8}$$

$$= V_E - R_{in} \cdot I_B \tag{3-9}$$

where:

V_B = terminal voltage [V]

V_E = equilibium voltage [V]

V_{in} = internal loss voltage [V]

R_{in} = internal resistance [Ω]
I_B = discharge current [A]

Obviously, higher discharge current results in reduction of the terminal voltage. Therefore, to specify the state of the battery by the battery voltage, discharge current should be also measured.

State of Charge

The state of charge (SOC) indicates how much charge is available in the battery referring to its capacity. This definition includes a degree of ambiguity, because the capacity can carry different values, either the nominal capacity, or the actual capacity. The interest two definitions are the following:

- *State of charge (SOC):* is the ratio between the difference of the rated capacity on the one hand and the charge balance on the other hand, as can be seen in equation (3-10).

$$SOC = \left(\frac{C_{nom} - Q_{Bat}}{C_{nom}} \right) \quad (3\text{-}10)$$

where: $Q_{Bat} = \int_t I dt$

C_{nom} = the nominal capacity of the battery [Ah] (i.e. *C10*)
Q_{Bat} = the Ah-balance (i.e. net Ah discharged or charged since the last full state of charge)
I = main reaction current [A]

- *Relative state of charge*: is the ratio between the difference of the actual capacity on the one hand and the charge balance on the other hand, as can be seen in the following equation (3.11).

$$\text{SOC} = \left(\frac{C_{act} - Q_{Bat}}{C_{act}} \right) \quad (3\text{-}11)$$

where:

C_{act} = the actual capacity of the battery [Ah]. This definition is used throughout this work.

The ability to determine the battery state of charge in a system at any time is very important from the point of view of the system operation. Knowing the state of charge continuously makes the system energy management possible. In addition, for a stand-alone photovoltaic system, the required battery capacity can be more accurately determined which implies higher reliability of the energy supply and lower system cost [12].

Gassing

With 2.3 – 2.4 V, namely the so-called *gassing voltage*, gas is developed at the electrodes in the battery, by which the water is decomposed into hydrogen and oxygen. Both gases mix together in the battery providing detonating gas (explosive!) and escape through ventilation opening in the vent plug. With the gassing, the battery loses also water, which must be refilled according to maintenance within regular intervals. The gas is the unwelcome secondary reaction of the chemical conversion during charging because current is consumed for the electrolysis and therefore the storage efficiency of the battery is made worse unnecessarily.

Continually, heavy gassing damages the battery, so that in the data sheet the manufacturers give the so-called *maximum charge voltage*, which is not allowed to be exceeded during charging. This voltage is situated about 2.3 – 2.4 V per cell (with 20 °C) corresponding to 13.8 – 14.4 V for 6 cells. In many battery types, small gassing for a short time is however required to mix the electrolyte and to provide an equal acid concentration for whole cell volume [5]

Freezing Electrolyte

For applications with low ambient temperature, the lead-acid battery must also be protected against freezing of electrolyte. The risk of freezing depends on the state of charge. Figure 3-12 illustrates the freezing limit as a function of the state of charge.

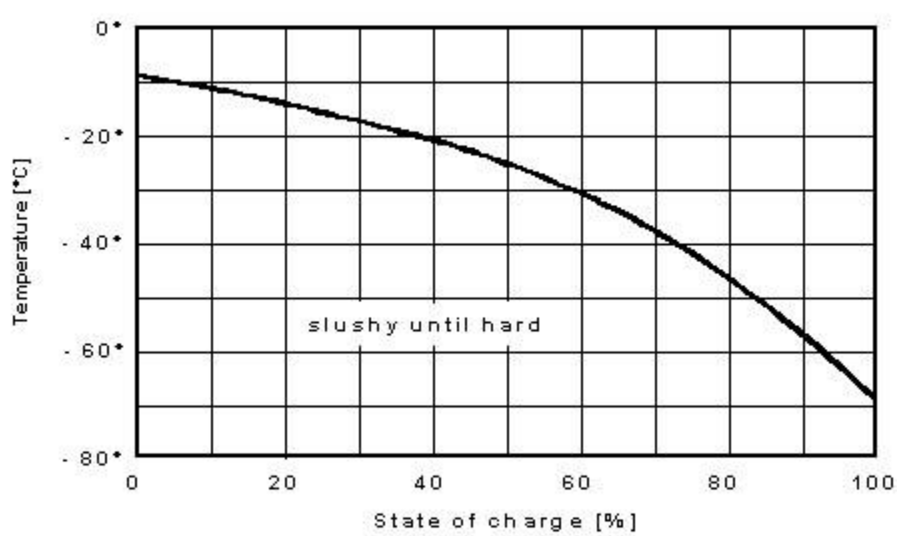

Figure 3-12: Freezing Limit as Function of State of Charge

Figure 3-13 illustrates current-voltage characteristics and working points of a battery, which is directly connected to 2 different ohmic loads by assuming that SOC and temperature of the battery are constant. A distance between the green line and dash line corresponds to V_{in}.

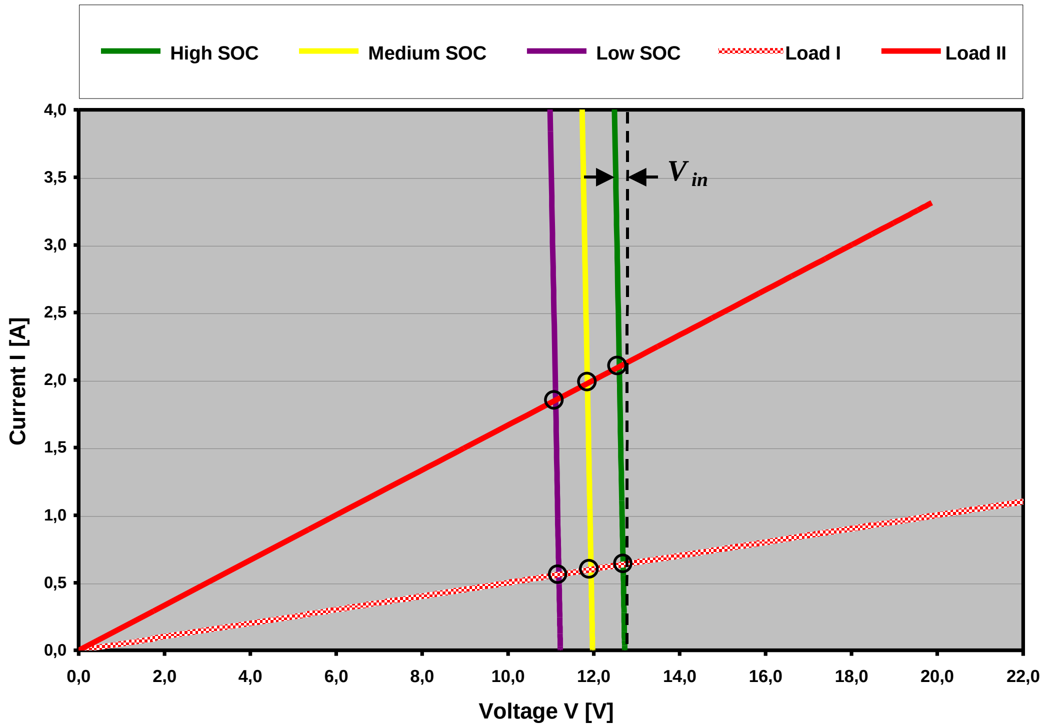

Figure 3-13: Working Points of Battery for Different Ohmic Loads [5]

Requirements for the solar batteries [5]

Typical requirements for the battery to be used for long-term storages are:

- low specific kWh-cost, i.e. the stored kWh of the battery
- long lifetime
- high overall efficiency
- very low self-discharge
- low maintenance cost
- easy installation and operation

Specific kWh-cost (DM/kWh$_{\Sigma}$)

Usually it refers to a sum of investment- and operation costs of the battery divided by the stored kWh (kWh$_{\Sigma}$) during its whole life. This cost is thus influenced by the battery's lifetime.

Lifetime

The lifetime of the battery should be long, especially in order to keep the specific kWh-cost and the installation cost low, particularly in remote areas.

Overall efficiency

The overall efficiency (η_{Σ}) is derived from charge- or coulombic efficiency (η_I) and voltage efficiency (η_V):

$$\eta_{\Sigma} = \eta_I \cdot \eta_V \qquad (3\text{-}12)$$

The coulombic efficiency is usually measured at a constant discharge rate referring to the amount of charge able to be recalled from the battery (Q_D) relative to the amount put in during charging (Q_C). Self-discharge will affect coulombic efficiency. Furthermore, it is reduced particularly by the secondary reaction during charging, i.e. gassing.

$$\eta_I = Q_D / Q_C \qquad (3\text{-}13)$$

The battery will usually need more charge than was taken out to fill it back up to its starting point. Typical average coulombic efficiencies are 80 – 85 % for stand-alone PV systems, with winter efficiencies increasing to 90 – 95 %, due to higher coulombic efficiencies when the battery is at a lower state of charge and most of the charge going straight to the load, rather than into the batteries.

The voltage efficiency, which is determined by the average discharge voltage (V_D) and average charging voltage (V_C), is lowered particularly by internal resistance of the battery. It is also measured at a constant discharge rate and reflecting the fact that charge is recalled from the battery at a lower voltage than was necessary to put the charge into the battery.

$$\eta_V = V_D / V_C \qquad (3\text{-}14)$$

η_{Σ} should be as high as possible, to be able to pass the biggest proportion of the energy in the battery, which is generated by the PV generator, further to consumers [7].

Self-discharge

The battery discharges itself even without load connected. This effect is caused by secondary reactions at it electrodes and proceeds faster with higher temperature or older battery. Thermodynamic instability of the active materials and electrolytes as well as internal- and external short-circuits lead to capacity losses, which are defined as self-discharge. This loss should be small, particularly according to annual storage.

Maintenance cost

The maintenance, e.g. water refilling in case of lead-acid batteries, should be kept as low as possible.

Easy installation and operation

Since batteries are driven often also from non-experts. Easy installation and operation are therefore favorable.

Power

In special cases battery must be highly loadable for a short time, e.g. at the start of diesel generators or in case of momentary power extension of PV systems [7].

3.2.3 Diesel Generator [13]

Most diesel generators used in Hybrid Systems are synchronous alternators directly coupled to regular diesel engine. Operating speed is controlled by adjusting fuel flow into the engine, which determines the frequency of AC output voltage. It is common known that:

- Diesel generator operating cost is governed by fuel consumption.
- The maintenance cost depends on operating hours and loading of engine.
- Frequent starting of diesel generator increase the mechanical wear replacement.

Therefore, for costs minimizing purpose, the following hint wise for diesel engine operation requirements are then suggested:

- Once diesel engine started, it should run for a minimum time period, typically at least 20 minutes of continuous operation. This specification is implemented to reduce engine wear replacements and to minimize maintenance costs.

- Do not allow to operating diesel engine below a minimum power level, typically minimum load is selected as 40% of its rate full load power. This suggestion is used to prevent “glazing” on cylinder walls and avoid low efficiency operation.

3.2.4 Charge Controller [14]

The main task of a charge controller is to prevent battery by limiting overcharging and deep discharging during operation. Further more. A charge controller can take over automatic and regular maintenance duties to prevent acid stratification. Advance charge controllers have system monitoring feature to inform the user on the stage of charge of battery. Some can record battery history e.g. number of deep discharge periods, Ah balance. In larger hybrid systems, the charge controller acts as an Energy Management System (EMS) that automatically starts back up diesel generator when the battery’s state of charge drops below limits.

3.2.5 Inverter

PV array generate only direct current (DC) electricity. Fortunately, most commercial electric devices need an alternating voltage (AC). Therefore, power-conditioning elements, which are commonly called “inverters” because they invert the polarity of the source in the rhythm of the AC frequency, are often applied to PV systems. Also in grid-connected systems inverters are basically necessary for the conversion of DC power into grid-compatible AC power.

Inverter efficiency is generally 80%-90% depending on the inverter type.

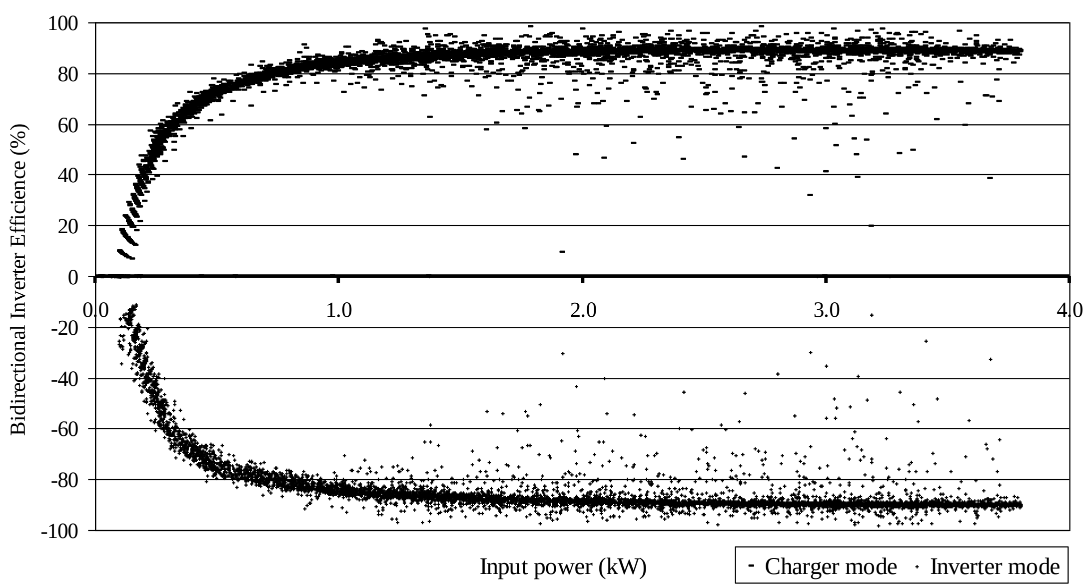

Figure 3-14: Bidirectional Inverter efficiency versus input power [27]

In figure 3-14 show relation of input power and efficiency of bidirectional inverter, above x axis is charger mode and under x axis is inverter mode.

The inverter is normally only single phase for small power rating. The three phase inverter is more expensive, which is use to serve higher power rating and unbalanced loads. For the DC/AC bus system with renewable and battery back up sources, it is recommend to select small single phase inverter to operate household equipments.

General working

The harmonic distortion of inverter becomes a significant issue especially when appliances like computers and refrigerators are connected. Inverter output waveforms shape can be square wave, modified sine wave or sine wave, which are an indication of the quality and cost of the inverter. Square wave and quasi-square inverters will introduce distortion comparing to a 50 Hz sine wave, but those are a lot cheaper than sine wave inverters.

Square wave inverter can be used suitably for power resistive loads such as resistance heaters or incandescent lumps.

Modified sine wave or quasi-sine wave inverters produce multiple steps square waveform that closely approximates a pure sine wave. This type of inverter is acceptable to supply most AC appliances and motors. However, some sensitive electronic devices may require sine wave inverter. These inverters can produce utility grade power but certainly cost more than the other types of inverters.

Inverters used in off-grid applications are electronic devices based on high frequency switching. In sine wave inverters, an internally generated sine wave is digitally produced at 50 Hz as a reference and this is used to create periodic train of pulse-width modulated voltages. This periodic train controls the switching of transistors such that the DC source is connected and disconnected accordingly. This is amplified the magnitude through a transformer (usually 230 V) and filtered to become a sine wave voltage output at 50Hz.

In normal operation, an inverter will shut down once its output upper limit is exceeded but modern inverters are designed in the way that they can handle power surges for a limited duration in order to minimize the heat build-up in switched and transformer. Typically, heat-limited inverters can supply over rated capacity for 30 minutes for such applications as starting induction motors.

3.3 Approach to Typically PV-Diesel Hybrid Systems Design

Many practical hybrid system designs and implementations are often based on experiences, trail and error. Monitoring studies can report problems, design corrections and requirement after installation. These criteria can perform poorly and costly, especially in remote area in developing countries.

The approach to design hybrid system can be presented in the following methods.

- Rule of thumb methods
- Ah method
- Spreadsheet methods
- Helper hybrid design software

Hybrid system design in this work will follow rule of thumb methods. Therefore the basic thumb rules will then be briefly described.

3.4 Rule of Thumb Methods

Rules of thumb give practical guidelines how to size and operate a hybrid system based on experiences with installed systems. This method requires input in the following [15]:

- Global irradiation: worst day and average per year
- Yearly electricity demand
- Maximum power of the total loads

To provide the following output:

- Peak power of PV generator
- Battery capacity
- Size of the diesel generator
- Size of the inverter

Load Analysis

The first step to design PV diesel hybrid system is to determine the electrical loads. The useful list of all possible household appliances and its consumption are served in Table 3-1 as guideline to estimate the actual loads.

Table 3-1: Annual Energy Consumption of Household Appliances [5]

Appliance	Power rating [W]	Daily consumption [kWh/d]	Annual consumption [kWh/a]
1 Incandescent bulb	60	0.25	90
1 Typical fluorescent lamp	40	0.15	60
1 Compact fluorescent lamp (CFL)	15	0.07	25
1 Fan, circulating	85	0.15	60
1 Fan, attic	375	0.75	270
1 Radio	55	0.10	35
1 Television, colour 19″	80	0.14	50
1 Sewing machine	75	-	4
1 Drill, 318″ variable	240	-	10
1 Blender/Mixer	350	0.07	25
1 Refrigerator (12cu. ft./340 litre)	330	2.75	1000
1 Vacuum cleaner	900	-	45
1 Iron	1000	-	50
1 Clothes dryer, gas	500	-	100
1 Clothes washer	1150	-	120
1 Toaster	1200	0.12	45
1 Hair dryer	1500	0.33	120
1 Microwave oven	2100	0.35	130

PV generator

By seen of the solar potential and the energy demand, it is possible to size a suitable PV generator to supply to the system with sufficient energy. The energy balance of the system should be generally determined as follows:

$$\mathbf{E_{demand} \leq E_{supply}}$$

Due to the uncertainty prediction of demand and the assumed solar radiation, the energy supply should be basically higher than the energy demand. However, it could sometimes happen that the supply could not meet the demand and the system fails consequently. For this reason, a *quality factor (Q)* is commonly used to present how well the supply meets the demand.

The quality factor is defined as the quotient of the real electric output energy measured at the system output (E_{el}), which is normally equivalent to the system load and the theoretical output energy (E_{th}), which is defined as the output energy from the same system under ideal conditions, i.e. Standard Test Conditions (STC: I_{STC} = 1000 W/m^2; T_{STC} = 25 °C, AM = 1.5):

$$Q = \frac{E_{el}}{E_{th}} \tag{3-15}$$

where:

Q	=	quality factor of the system
E_{el}	=	real electric output energy of the system [kWh]
E_{th}	=	theoretical output energy of the system [kWh]

The quality factor can be determined over any given time period. In most cases, a time period of one year is chosen to pre-size PV systems.

The theoretical output energy (E_{th}) is defined as the energy output, which is produced by a PV array with an area of A_{array}, the global radiation E_{glob} incident on a horizontal surface and efficiency η determined under STC:

$$E_{th} = \eta \cdot E_{glob} \cdot A_{array} \tag{3-16}$$

where:

E_{th}	=	theoretical output energy of the PV array [kWh]
η	=	efficiency of the PV array [decimal]
E_{glob}	=	global radiation on a horizontal surface [kWh/m^2]
A_{array}	=	area of the PV array [m^2]

It is often difficult to obtain values like the efficiencies from manufacturers. Besides, the area of the array is frequently unknown. However, the peak power measured under STC is normally given

$$P_{peak} = \eta \cdot I_{STC} \cdot A_{array} \tag{3-17}$$

where:

P_{peak} = peak power of the PV array [kW_p]
η = efficiency of the PV array [decimal]
I_{STC} = incident global radiation under STC [1 kW/m^2]
A_{array} = area of the PV array [m^2]

According to the equations (3-16) and (3-17) after substitution of $\eta \cdot A_{array}$:

$$E_{th} = P_{peak} \cdot \frac{E_{glob}}{I_{STC}} \tag{3-18}$$

According to the equations (3-15) and (3-18) the quality factor can be found out:

$$Q = \frac{E_{el}}{E_{glob} \cdot P_{peak}} \cdot I_{STC} \tag{3-19}$$

With the quality factor formula above and the empirical quality factors of existing systems it is easy to pre-size the PV array:

$$P_{peak} = \frac{E_{el} \cdot I_{STC}}{E_{glob} \cdot Q} \tag{3-20}$$

In the theoretical limiting case, supply and demand values are equivalent and the quality factor is therefore equal to one (Q = 1). A measured value of, for example, Q = 0.75 means that 75 % of the electric energy, which is converted from the incident solar energy, is used whereas 25 % of the electric energy is lost between the solar cell and the system output or it is not used.

The quality factor depends strongly on the system type. In case of grid-connected systems all produced energy could be used, so there will never be surplus energy. In a PV system it could however happen that the battery storage is full and then PV energy will be dissipated. For this reason, the quality factor relates to the system type. The guideline to design the system type with the amount of energy consumption is in Table 3-2. The quality factors are given in Table 3-3.

Table 3-2: **Suitable Type of PV Systems and Alternatives Depending on Regular Energy Consumption [5]**

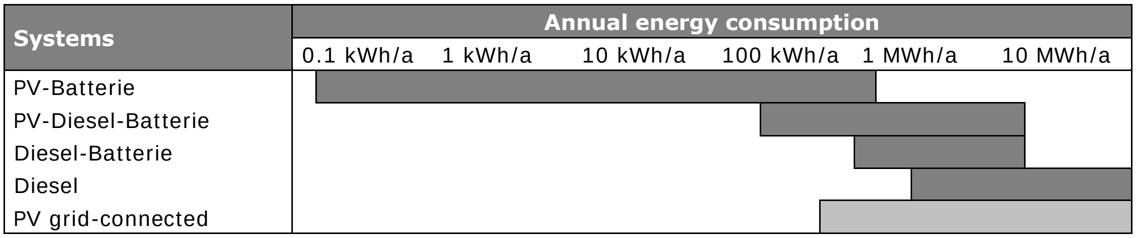

Table 3-3: Quality Factors of Components and Different PV Systems [2]

Component/System	*Q*
PV module (Crystalline)	0.85...0.95
PV array	0.80...0.90
PV system (Grid-connected)	0.60...0.75
PV system (Stand-alone)	0.10...0.40
Hybrid system (PV-Diesel)	0.40...0.60

Battery sizing

The battery capacity depends on characteristics of radiation, load, and system reliability as well as intention of the user. By experience, the relation between battery capacity [kWh] and peak power [kW_p] of the PV array is more or less 10:1. In case that the global radiation at the site is nearly constant throughout the year, this value will be lower than 10:1. When having a system where the power consumption is mainly during the night this thumb rule must be corrected to the value higher (up to 20 % more) and vice versa when e.g. a wind generator or a diesel generator is integrated into the system. This relation for some existing stand-alone systems is presented in Figure 3-14.

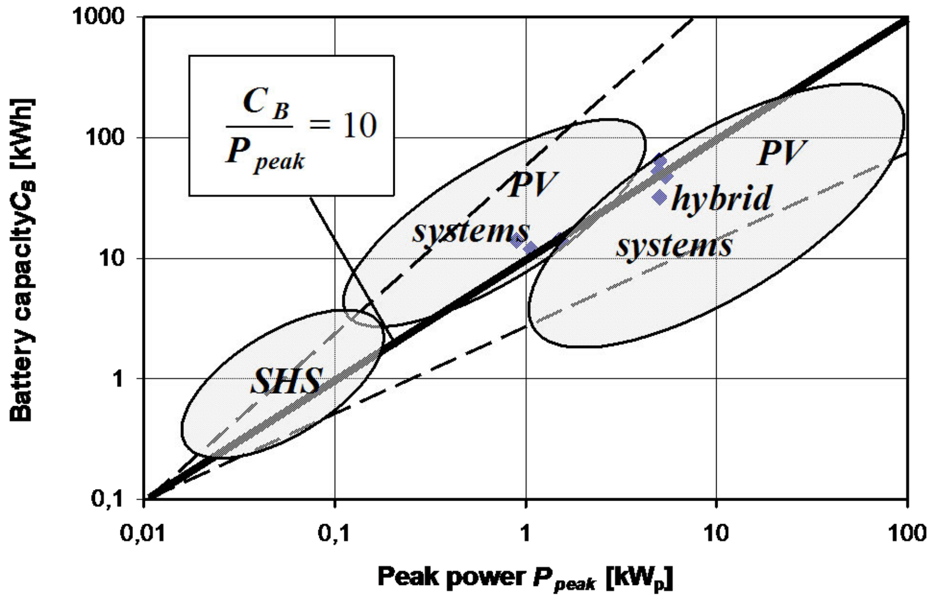

Figure 3-15: Thumb Rule for Relation of Battery Capacity and PV Nominal Power [5]

In hybrid system, the battery capacity is dimensioned based on experience is presented in equation (3-21). It equals t0 rated power multiply by 10 hours [15].

$$C_B = 10h \cdot P_{peak} \qquad (3\text{-}21)$$

where:

C_B = battery capacity [kWh]
P_{peak} = peak power of the PV array [kW$_p$]

By other expert recommendations, the size of battery can be one day of autonomy. That mean the battery capacity must be large storage enough to back up the system without charging at least one day. Some suggests 3-5 days of autonomy in hybrid system due to cost optimization. The smaller battery capacity is, the cheaper initial batter costs are. However, a smaller battery results in more frequent cycling and shorter battery life. The replacement costs can be increased. The decision around battery size and operation is on customer-driven.

In battery operation, a charging rule was mentioned should be above 85% state of charge (SOC), some suggests not being below 60% SOC (i.e. 40% depth of discharge) for lead acid batteries in hybrid system.

The battery capacity can be calculated also by the following formula:

$$C_B = \frac{N_d \cdot E_{y,load}}{DOD \cdot \eta_{inv}} \qquad (3\text{-}22)$$

where:

N_d	=	number days of battery autonomy, [day]
$E_{y,.load}$	=	yearly daily-average load demand, [kWh/day]
DOD	=	battery depth of discharge, [%]
η_{inv}	=	inverter efficiency, [%]

From the above formula, the size of the battery depends on the number days of battery autonomy *(N_d)* and maximum depth of discharge (DOD).

Diesel Generator

Since reliability is important, the diesel generator should be sized to cover full load. However, customers often do not want to pay much for such high reliability. The decision around diesel generator size and operation hour is again customer-driven due to its high costs impact [14].

It was recommended on diesel generator operation by hybrid system expert to allow running diesel generator sometimes supplying the load. Different views were expressed on suitable diesel operation times, e.g. run diesel once every 3-5 days, once a day, or every morning and afternoon. Some suggested minimum diesel generator running time is 30 minutes. Some recommended stopping diesel generator once load drops below 50% in order to improve life cycle costs.

Inverter

The Inverter needs to be sized to cover the peak load that must be able to supply during most hours of the day. The surge currents can be up to 3-6 times of the normal current. Some experts or books recommend sizing the inverter for peak demand plus an extra 20%-30% [14].

In general, the use of sine wave inverter is more recommended instead of a square wave inverter.

Merit of Rules of thumb methods

Rule of thumb methods are easy to use design guidelines derived from experiences. They require not much based information to provide a quick system design. However, they do have limitations that they can only give broad recommendations and results are not optimized solutions due to only rough estimation which lead a high degree of uncertainty.

However, when planning a PV system, consumer load is much more uncertain factor and experience has shown that the empirical method provides as good results as when the system is sized by simulation programs.

3.5 Summary

The PV-Diesel hybrid system is the combination of 2 energy sources; 1. PV Array to produce DC power and 2. Diesel generator to produce AC power which can alternative generate electricity supply to the load, while exceeds energy is backed up in battery storage.

The most common hybrid configurations and its operation principles which are; 1. Series hybrid energy system, 2. Switch hybrid energy system and 3. Parallel hybrid energy systems were described in chapter 3.1.

The main components of PV-Diesel hybrid system are; 1. PV-Modules, 2. Battery bank, 3. Diesel generator, 4. Charge controller and 5. Inverter were fundamentally discussed in chapter 3.2.

Rule of thumb methods were introduced in chapter 3.4 in order to be the quick guidelines for sizing and operating hybrid system.

Chapter 4 : PV-Bio Diesel from a Farmer Diesel Engine for Hybrid Solar Home Systems [PV-Bio FDE for HSHS]

4.1 Introduction to PV-Bio FDE for HSHS Project

Currently, Due to the renewable policy of the Ministry of Energy, Thai government dominantly issued policy to support funding to PV Solar Home System Project 120 W at remote area off the electrical grid with an amount of 300,000 households. Those actions are taken by Department of Alternative Energy Development and Energy Efficiency (DEDE). The first pilot project owned by PEA with 300,000 systems is going to install within the end 2003. Obviously, most of people at remote sites in Thailand are farmers engaging farming activities. They mostly own *"Farmer Diesel Engine (FDE)"*so called E-TAC with the power range of 8-12 HP and E-TAN with the power range of 12-25 HP.

Both engines are generally used for many purposes like; 1 farming, 2 pumping, 3 transportation and 4 household electricity generation. The use of Farmer Diesel Engine for generating electricity has still many problems like:

1. Using for generating electricity for 3-4 hours at nighttime after farming, which lead to long nighttime noise pollution.
2. Using diesel fuel, generate toxic emissions, lead to environmental impacts.
3. Using high fuel consumption while low efficiency energy.

Thus, the *"PV-Bio Diesel from a Farmer Diesel Engine for Hybrid Solar Home Systems"* is alternatively proposed in this thesis to develop the traditional use of FDE becomes manual multi-modes *Hybrid System* between PV and Farmer Diesel Engine coupling with AC Machine generating AC 220 V 50 Hz electricity. For the stability and reliability aspects, this system has to be designed different from other hybrid system as follow:

1. The use of Bio diesel from local farming activities.
2. The appropriate design supports multipurpose uses of Farmer Diesel Engine:
   - Daytime: farming, pumping and transportation
   - Nighttime: electricity generating
3. PV battery charging and back up by using bio-diesel engine.
4. Simple control and monitoring system for farmer.
5. Energy management with manual operation.

4.2 Inspirations of PV-Bio FDE for HSHS Project

This work is motivated by integrating the found key issues in the following:

- Attractive high potential of solar radiation in Thailand, which recognized as free energy source. As common know, Thailand yearly average daily solar radiation on the horizontal surface of about 5 kWh/m^2·day.
- Plenty of biomass resources in Thailand, which refine to Bio-diesel fuel.
- PV utilization of failed projects of installed PV-Systems such as PV battery charging station, PV pumping station etc.
- To create major benefits to almost 60%-70% of Thais population which are farmer doing agricultural activities in remote area.
- Thai farmer nowadays use Farmer Diesel Engine with power range of 8-12 HP as agricultural machine for various kind of farming activities in substitute of water buffalo.
- To utilize Farmer Diesel Engine by integrating in PV Hybrid system in order to enhance higher efficiency electricity generation and minimize major electricity cost by the use of diesel fuel.
- To design system which most custom fit to culture and life style of traditional Thai farmers using locally existing components for producing electricity supply to their households.

4.3 Traditional Thai Farmer Culture and Life Style

To design the appropriate generation system to be best suited to electricity use of farmers, it is needed to understand traditional Thai farmers' culture and life style.

- Ordinary Thai farmer child families are expanding their family with out splitting out of parent families.
- Family members after married normally build their house nearby and live together with older members in cluster home.
- Each cluster has 3-5 family members; there are leader parent house and child houses located in neighboring.
- Thai farmer family members and their relatives normally work together on the family's field in farming season.
- Today a universal "Farmer Diesel Engine (8-12 HP)" is a normal tool for working in the field to substitute of water buffalo, which had been widely used before.
- In non-electrified cluster, the parent house usually mutually act as single electricity provider to generate electricity by coupling FDE with AC Machine and supply to child houses.

4.4 Get to Know "Farmer Diesel Engine (FDE)"

Farmer Diesel Engine is an agricultural machine driven by a universal diesel engine at the range house power of 8-12 HP. It can couple with other equipment to use in several purposes. Nowadays, FDE becomes a normal tool for working in the field to substitute of water buffalo, which had been widely used before. Figure 4-1 shows Farmer Diesel Engine at power rate 12HP.

Figure 4-1: Farmer Diesel Engine (FDE)

4.4.1 Major Standard of FDE

Major standard of FDE categories in Thailand can be divided in the foloowing:

1. E-TAC: small to medium size of FDE. This engine type has power range 8 to 12 HP with single piston. Almost Thai farmers use this FDE power range for their agricultural activities.

2. E-TAN: medium to large size of FDE. This type has power range of 12 to 25 HP with 2-4 pistons.

4.4.2 Purposes of FDE

FDE are used in many purposes in the following:

1. Farming: FDE is put on the small pushcart equipped with gear system for farming in the field.
2. Pumping: FDE is coupling with mechanical pump for water irrigation.
3. Transportation: The carriage is connected with FDE for transportation.
4. Driving AC Machine for generating electricity use in their households.

The driven system when FDE is connected to other equipments is simple pulley welt drive system. Figure 4-2 presents the use of FDE in various purposes. As indicated number with description under the photos, the use of FDE are; 1 Farming, 2 Pumping, 3 Transportation and 4 Generate electricity accordingly.

1 farming

2 water pumping

3 transportation

4 couple with generator to generate electricity

Figure 4-2: Farmer Diesel Engine Usages in Many Purposes

4.5 300,000 PV Solar Home Systems Project 120 W

Since 3 June 2003, the Board of Ministry under Thai government dominantly issued policy to Ministry of Interior to promote PV Solar Home Systems Project 120 W at remote area off the electrical grid with an amount of 290,217 or approximately 300,000 households with in 2 years (2003-2005) in the total budget of 7,631,925,000 baht. Department of Alternative Energy Development and Energy Efficiency (DEDE) take those actions. The project owner is PEA. Project road map to 2005 with budget is presented in Table 4-1.

Table 4-1: SHS Project Road Map to 2005 with Its Budget [9]

Year	Households	Construction cost (Million baht)	Project Management Budgets	VAT (Million baht)	Interest of Loan	Grand Total (Million baht)
2004	153,000	3,825	191.25	267.750	3.782	4287.782
2005	50,000	1,250	-	87.50	-	1337.50
Total	203,000	5,075	191.25	335.250	3.782	5625.282

Figure 4-3: Solar Home System 120 W

The SHS project budget is subsidized by Thai government through Tambol Administrative Organization that allocated as follow:

- Budget on 2004 is allocated totally amount of 4,016,250,000 baht consists of construction cost 3,825,000,000 baht and 5 % of construction cost as project management with 191,250,000 baht. This budget covers SHS for 153,000 households. The SHS construction cost is 25,000 baht per household.
- Budget on 2005 is allocated totally amount of 3,615,045,000 baht consists of construction cost 3,442,900,000 baht and 5 % of construction cost as project management with 172,145,000 baht. This budget covers SHS for 153,000 households. The SHS construction cost is 25,000 baht per household.

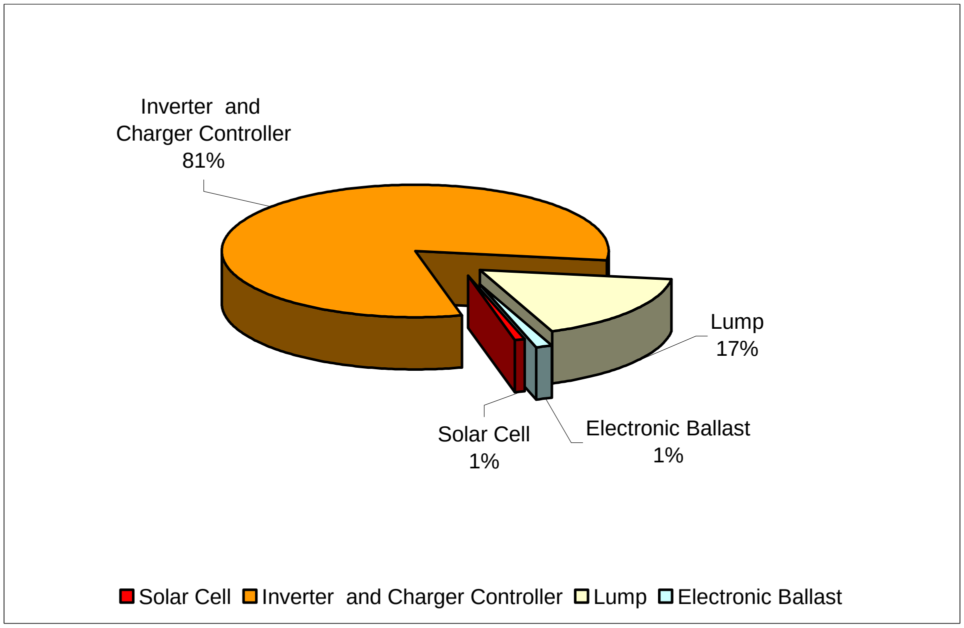

Figure 4-4: Defect Devices by Type in Solar Home System

Figure 4-3 presents the 120 W SHS have been installed to villager's house in many sites. The selected villagers are non-electrified households that located far from grid utility supply.

Recently, Project Owner, PEA has installed 74,659 Solar Home Systems (SHS) as of April 2005. Since SHS have been installed to villages, more than 1,291 systems were out of order. Major problems cause controller devices were defect as shown in pie graph in Figure 4-4.

4.5.1 System Components of 120 W Solar Home System

The main system components of 120 W SHS project that owned by PEA are in the following:

1. PV modules 120 Watts, efficiency 12%
2. Charge controller: 10 Amp, output voltage 12 V
3. Inverter 150 Watts
4. Battery: Deep Cycle 125 Ah 12 Volt
5. Fluorescent 10 W 2 sets
6. TV 14" 60 W 1 set

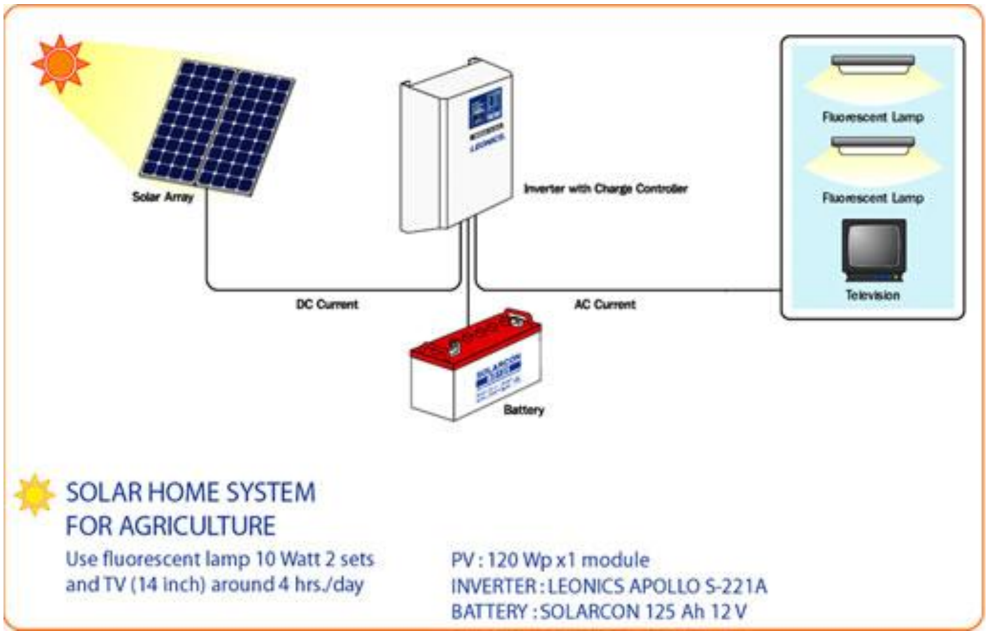

Figure 4-5: Solar Home System 120 W [10]

Figure 4-5 presents the system configuration of 120 W SHS with its components. This system can supply power 120 W_p. It is designed for load using just 2 sets of fluorescent lamp and 1 set of 14" Television around 4 hours a day.

4.5.2 Daily Energy Generated by SHS 120 W

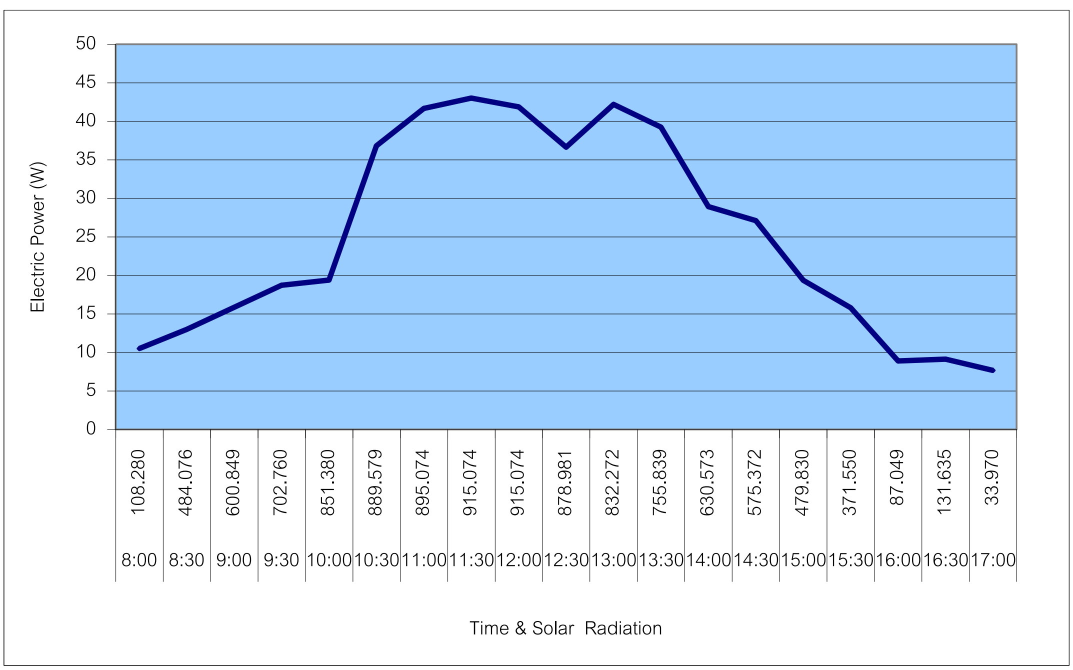

Figure 4-6: Daily Electricity Generated by Solar Home System 120W [9]

Table 4-2: Power Flow Generated by SHS 120 W

PV 120 Wp generate power 5 h/day	540.0 Wh
PV-Controller-Battery connecting loss ~ 5%	513.0 Wh
Loss if PV not using maximum voltage point to charger battery ~20%	
Power to charge battery	410.4 Wh
Design Array to Load Ration 1.3 : 1	315.7 Wh
Battery-Inverter-Load connecting loss 5%	299.9 Wh
DC to AC Inverter efficiency 80%	239.9 Wh
Power generated per day	**~ 240 Wh**

4.6 Bio-diesel in Thailand

Bio-diesel or ester is another alternative fuel for vehicles that can be either directly extracted like jatropha curcas linn oil or extracted from oil plants e.g. coconut, soy bean, palm via chemical process (Transesterification or Alcoholysis), using alkaline as a catalyst to transform fatty acid into ester or bio-diesel which has similar properties to those of diesel oil.

Energy Policy and Planning Office has prepared Thai Energy Strategic Plan from 2002-2011 under approval by Minister of Energy.

4.6.1 Bio-diesel under Thailand Energy Strategic Plan 2002 to 2011

1. Strategic Plan during 2002 – 2004:

   - Government promoted the research on bio-diesel extract form used cooking oil.
   - Government promoted the research to study the potential of other oil products especially from palm and coconut. The target of oil product in 2011 should be increased 1.33 times from year 2002.

2. Strategic Plan during 2005 – 2011:

   - The exceed palm oil from household utilization will be produced bio-diesel expected to be 20 % of palm oil in each year.
   - The exceed coconut from household utilization will be transformed to bio-diesel expected to be increased 1.33 times from 2001 to 2011.
   - The used cooking oil from food industries such as fast food and large restaurants with an amount of 42,000 liters per year will be totally used to produce bio-diesel.
   - Jatropha curcas linn seeds will be studied and researched on the engine impacts, economic and productivity. The prototype of operating bio-diesel factory will be started in 2007, 2008 to cover Jatropha curcas linn trees 5,000 and 7,000 Rais respectively. During 2009-2011, the areas of Jatropha Curcas Linn agriculture will be increased to 10,000 Rais.

4.6.2 Potential Raw Materials for Bio-Diesel Production in Thailand

1. The mixtures vary between diesel and ester extracted from palm oil.
2. The mixtures vary between diesel and ester extracted from coconut oil.
3. The mixtures vary between diesel and ester extracted from used cooking oil.
4. The extracted from Jatropha Curcas Linn oil.

4.6.3 Bio-Diesel from Jatropha Curcas Linn for Community Energy [28]

Jatropha Curcas Linn Tree

Jatropha Curcas Linn Tree is a middle shrubbery plant in a high range of 2-7 meters with life year at 25-30 years. Jatropha Curcas Linn green fruit color is light green and becomes yellow when it is ripe. Its seed size is 1.7-1.9 centimeters with 0.8 – 0.9 centimeters seed thickness.

Figure 4-7: Jatropha Curcas tree, fruit, and its seed.

Seed Products per Rai

- Native ancestors: normally, the seed products is 300-350 kg per Rai
- Selected ancestors: seed products after selection is700-800 kg per Rai
- Luang-Prabang blende ancestors: seed products after mix with Luang-Prabang ancestors is increased upto 1,500 kg per Rai

Jatropha Curcas Linn Oil Extract production

Jatropha Curcas Linn Oil extract production can be categorized in 3 types:

- Extraction in Laboratory: with this production, the extracted oil is 34.3 % from seed.
- Extraction by hydraulic pressing machine: with this production, the extracted oil is 25-30% from seed.
- Extraction by screw pressing machine: with this production, the extracted oil is 25-30% from seed.

In Thailand, the extracted oil from Jatropha Curcas Linn is the most appropriate and convenience use for the people in the rural areas because

- Jatropha Curcas Linn oil from pressing machine can be directly used in the farmer diesel engines without any mixture with other kind of oils.
- It does not need standard for engine adjustment and friendly environment.

The comparison of Jatropha Curcas oil and Diesel oil consumption are presented in Table 4-3

Table 4-3: Comparison of Jatropha Curcas Linn Oil and Diesel Oil Consumption

Engine Operation (rpm)	Jatropha Curcas Linn Oil Consumption (c.c./hr)	Diesel Oil Consumption (c.c./hr)
1500	**489**	**500**
1600	494	498
1700	528	540
1800	576	586
1900	614	629
2000	**665**	**696**
2100	720	758
2200	770	804
2300	**852**	**869**

Table 4-4: Environment Impact Comparison between Jatropha Curacas Linn Oil and Diesel Oil

	Jatropha Curacas Linn Oil	Diesel Oil
Smoke	13.42%	13.67%
CO	587 ppm	587 ppm
SO_2	Not found	Found (125 ppm)

4.7 Farmers' Electricity Need after SHS Installation

Basic need for farmer life is lighting and water. When they have electrical connected, they would like to have more electric appliances to serve their life comfort e.g. color television, CD player water pump, rice cooker and refrigerator.

Significant concern in this work is that what can be done for SHS 120 W_p can supply energy just *"240 Wh / day"*.

4.8 Innovative Thinking Concept to PV-Bio FDE for HSHS Project

As outlined in earlier section, PV-Bio FDE for HSHS Project is the development of new hybrid concept design which is attempted to supply rural electricity needs with a cost-effective, socially acceptable, traditionally adaptable, and environmentally congenial manner by using existing local devices and know-how technologies. In this innovative hybrid concept, the Farmer Diesel Engine(FDE) is then presented to replace normal diesel engine for the following reasons:

- Savings in time, developing IN-HAND and IN-LAND technologies.
- Savings in costs, using and modifying existing rural equipment.
- Savings environment, reducing environmental impacts by utilizing bio-diesel fuel.

In this PV-Bio FDE for HSHS Project, it is assumed that the target households in villages are located in a rural region would not be able to obtain grid-supplied electricity. This target groups being considered are farmers who own " Farmer Diesel Engine " and want to generate themselves AC electricity mainly used for lighting and low load household appliances like radios, television sets, cassette players and so on.

Target Group PV-Bio FDE for HSHS Project is illustrative shown in Figure 4-7. This work focus on farmer family who own FDE have non-grid-supplied electricity and want to generate electricity.

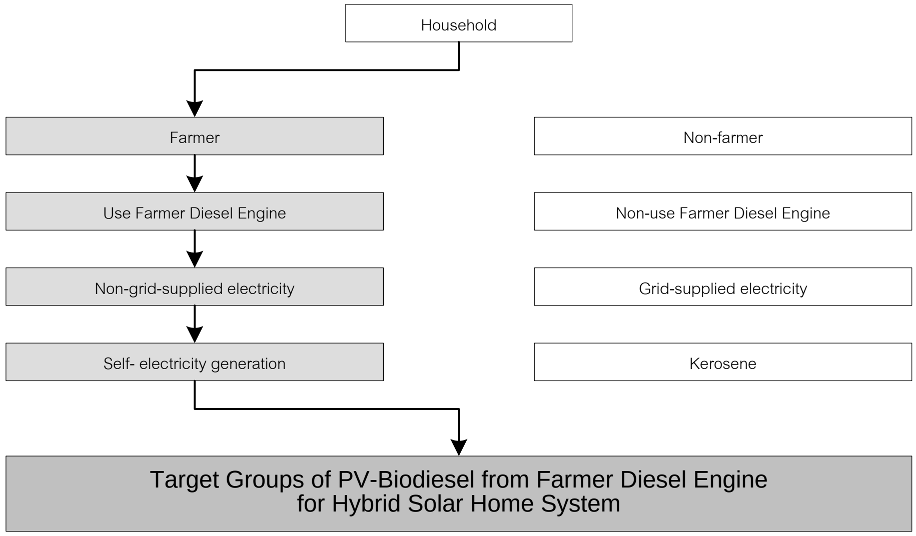

Figure 4-8: Target Group of PV-Bio FDE for HSHS Project

4.9 PV-Bio FDE for HSHS Project in Phichit Province

Since target group of PV-Bio FDE for HSHS Project has been clearly defined, the demo site to demonstrate system should be then selected. The selected farmer family to install the prototype of PV-Bio FDE for HSHS is farmer family in Phichit Province which located 60 kilometers from Phitsanulok in the north of Thailand.

Figure 4-9: Site Location to Install PV-Bio FDE for HSHS in Phichit, Thailand [26]

4.9.1 Farmer Households Load Survey

As common known, the first step in designing such a PV or Hybrid systems is to determined load. Farmer households load survey has been done in order to: 1. Foreseen regular electric appliances use, 2. Estimate the rated power and energy demand of the actual load.

By survey, it is found that the energy demand of usual farmer households in Phichit can be categorized in 3 levels:

- Small energy demand in the range of 300 – 1,000 Wh/day
- Medium energy demand in the range of 1,001 – 2,000 Wh/day
- High energy demand is greater than 2,000 Wh/day

4.9.2 Cluster of Selected Farmer Family in Phichit

As mentioned in 4.3 Traditional Thai farmer culture and life style, ordinary Thai farmer family are expanding family members which is called "*Child*" normally build their houses and live close together with older members which is called "*Parent*" in cluster home. Each cluster has 3-5 family members. Family members and their relative normally work together on the family's field.

This selected cluster of Phichit farmer family has 3 households living in neighboring. Both of 2 "*Child houses*" were built 60 meters and 70 meters close to "*Parent house*" as can be seen in Figure 4-9.

1 location plan of 3 house cluster

2 picture of parent house

Figure 4-10: Cluster of Selected Farmer Family in Phichit

4.9.3 Conceptual Design of PV-Bio FDE for HSHS Project

Traditionally, in rural communities live without grid-supply electricity generated electricity by using FDE driven-generator. Our interest is the farmers who have FDE. Most of them commonly couple this engine directly to AC Machine producing electricity in the nighttime. The parent house is normally the single provider generated electricity and then supply to its child house in cluster home.

Engine driven generators are rather inefficient when operate at light load, which can also shorten their operating life and result in high maintenance costs. Further more, diesel only system leads to more environmental impacts like noise and air pollution.

Considering on energy uses nowadays, the utilization of renewable energy sources for remote area power generation are increasing, in some remote areas in some countries are utilizing power from sun, wind and hydro by using PV modules, wind generator and hydro-electric generator.

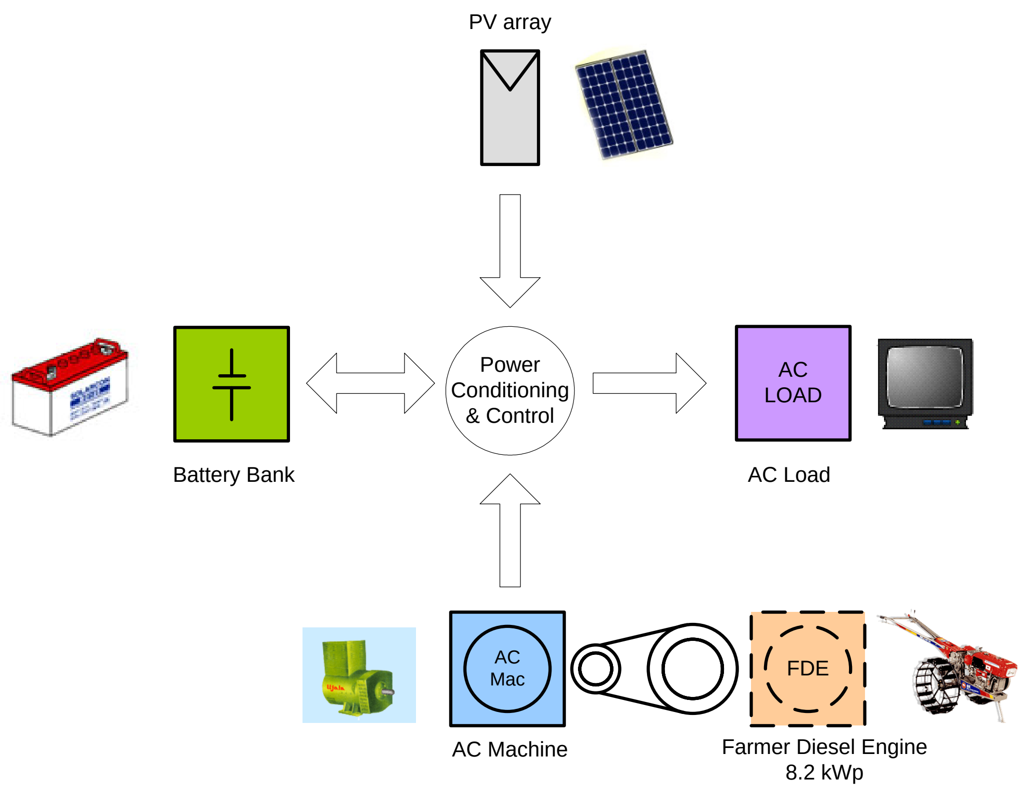

Figure 4-11: Hybrid System Conceptual Design

PV-Bio FDE for HSHS is an innovative concept of manual-switched hybrid system combining renewable energy source from sun using PV and conventional energy source by coupling existing FDE using bio diesel with AC Machine and back up battery bank to improve the stability and reliability of the overall power system for farmer family in cluster. The Figure 4-10 shows conceptual design.

4.9.4 System Design Considerations

System Design Considerations for the selected cluster of farmer family with 3 households in Phichit, we consider utilizing most farmers' in hand technology and developing to meet the optimum. The methodology to design and select system components can be different from standard PV sizing procedures. In this work, design process steps are; 1 Load analysis by determining the total power of load and energy demand, 2 Firstly consider utilizing the existing farmer's components, 3 Rough sizing, 4 Detailed design and Selecting components.

Determining load in load estimation sheet

Table 4-5: Load Estimation Table of Selected Farmer Family in Phichit

Appliance	AC / DC	Units	Power (W)/unit	Duty cycle (h/day)	Total Power (W)	Energy Demand (Wh/day)
Lump	AC	10	15	4	150	600
TV 21″	AC	1	80	2	80	160
TV 14″	AC	1	60	3	60	180
Fan	AC	3	60	5	180	900
CD Player	AC	1	80	2	80	160
Rice cooker	AC	1	600	1/2	600	300
Other					100	100
TOTAL					1,250	2,400

Existing Farmer Diesel Engine & AC Machine

This cluster of farmer family has existing FDE at 11 HP (8.2 kW_p) and AC Machine with rated power 3 kVA. Thus, the sizings of FDE and AC Machine have to be anyway at this power rate fixed.

Existing PV modules

Aligned on concept to replace and further develop from 300,000 Solar Home System government project to hybrid integration, PV- Modules will be selected in according to PV-Modules from Solar Home System. Prototype of PV-Bio FDE for HSHS consists of 3 households: 1 parent house and 2 child houses. Thus PV-modules 120 W of each in combination are 360 W. By assumption that PV-modules are old lead to low efficiency drop, therefore compensation factor of

20% should be applied. Thus, the recommended PV-Modules should be about 432 W.

To demonstrate the system closely to assumption, this work will then use PV-modules 53 W with number of 8 modules in totally approximate 424 W.

Bi – directional Inverter

Result by load estimation table of selected farmer family in Phichit, the total watt peak of this cluster is 1,250 W; the recommendation to select inverter at rated at least 20% more than the maximum power requirement of the load is applied. Then Bi – directional Inverter at rated power 1.5 kVA is selected.

Battery capacity

As discussed in rules of thumb methods in chapter 3, the design battery capacity in this work follows a multiple of 10 hours power peak of PV. Then battery capacity should be in the range of 4,240 Wh.

Charge Controller

The charge controller should be select according to the DC power and the battery charging requirements. The battery charger output must not exceed the maximum charging rate of the battery, but it must be as large as possible in order to minimize the running time of the generator. The details will be described later.

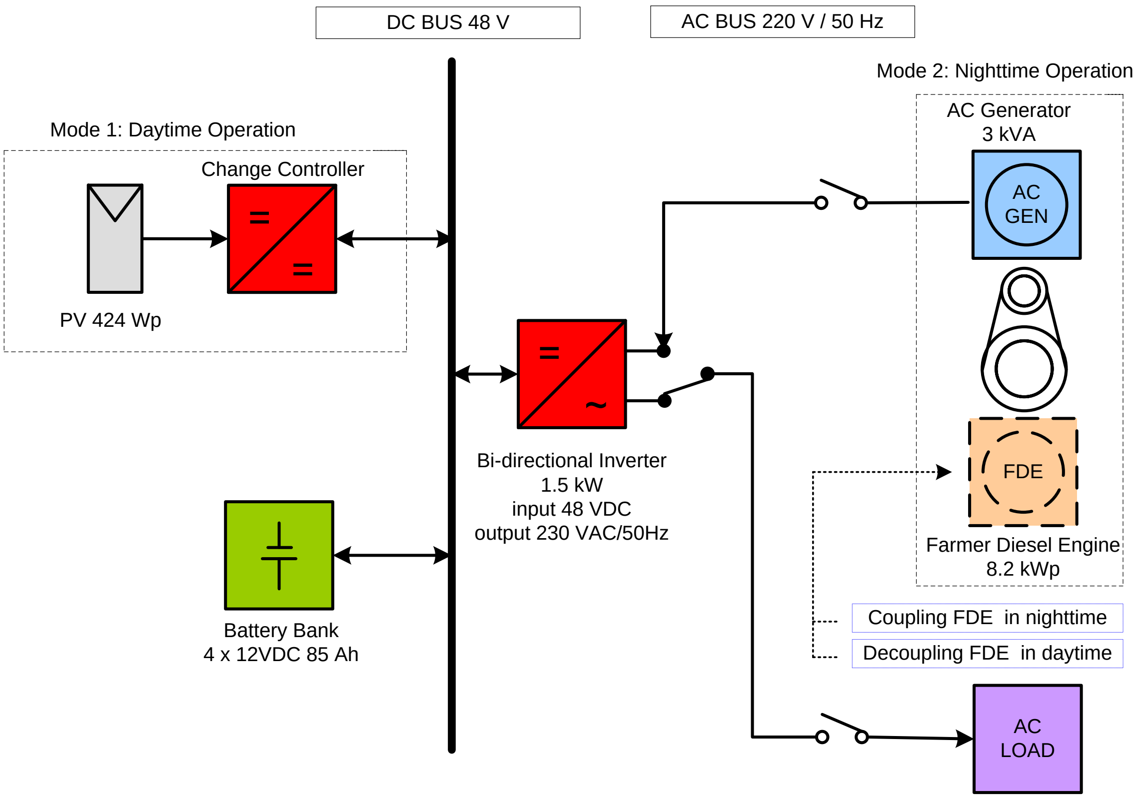

Figure 4-12: Conceptual Diagram of PV-Bio Diesel from Farmer Diesel Engine for Hybrid Solar Home System

4.9.5 Mode Operational Principle of PV-Bio FDE for HSHS

This system generates AC 220 V/ 50 Hz electricity by combining PV array with an inverter, operate alternately with Farmer Diesel Engine driven AC Machine with a battery bank for storage. The design concept allows operation in 2 modes:

Mode 1: Daytime operation allows PV array generating power from sun in the daytime. Since there is power flow from PV generator in daytime, Bi-directional will operate in *inverter mode*, internally, automatic switch will transfer power to supply AC load, while the power exceeds load demand are charged in the batteries controlling by controller.

Mode 2: Nighttime Operation allows Farmer Diesel Engine driven AC Machine to generate power by utilizing Bio diesel fuel in the nighttime. Once the Farmer Diesel Engine that coupling with AC Machine was started in RPM range that generate voltage in the range of 176-265 Vac, Bi-directional will operate in *charge mode,* automatic switch in Bi-directional Inverter will be transferred to connect AC load directly to AC Machine. The AC load can be then supplied directly by Farmer Diesel Engine driven AC Machine. Typically, the AC Machine power will exceed the load demand, and then the excess energy will be used to recharge the battery bank.

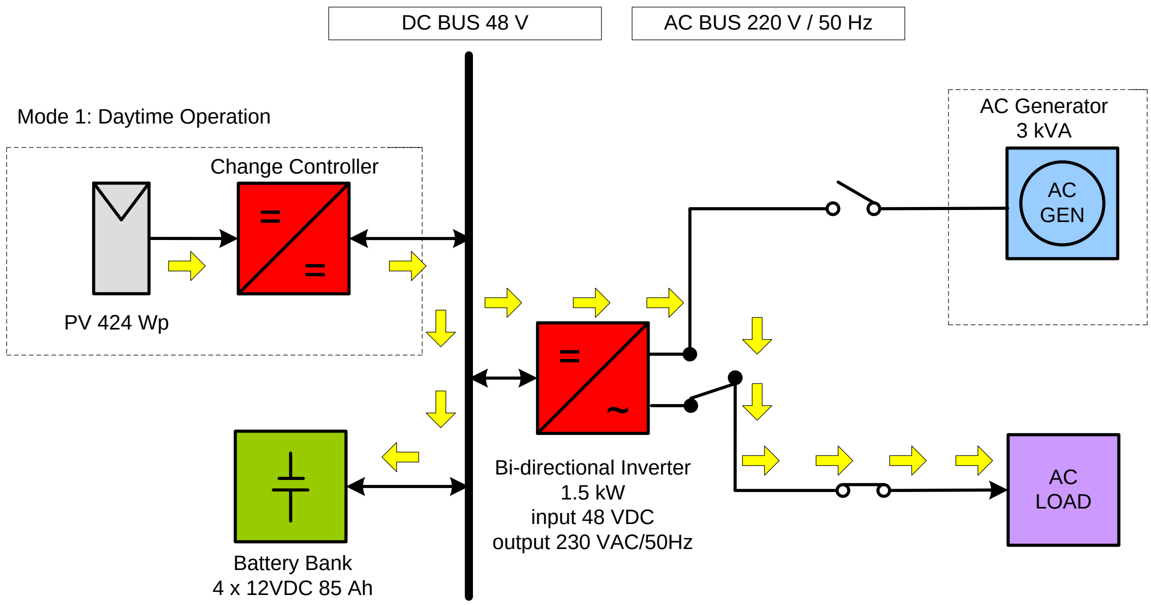

Figure 4-13: Mode 1: Daytime Operation of PV-Bio FDE for HSHS

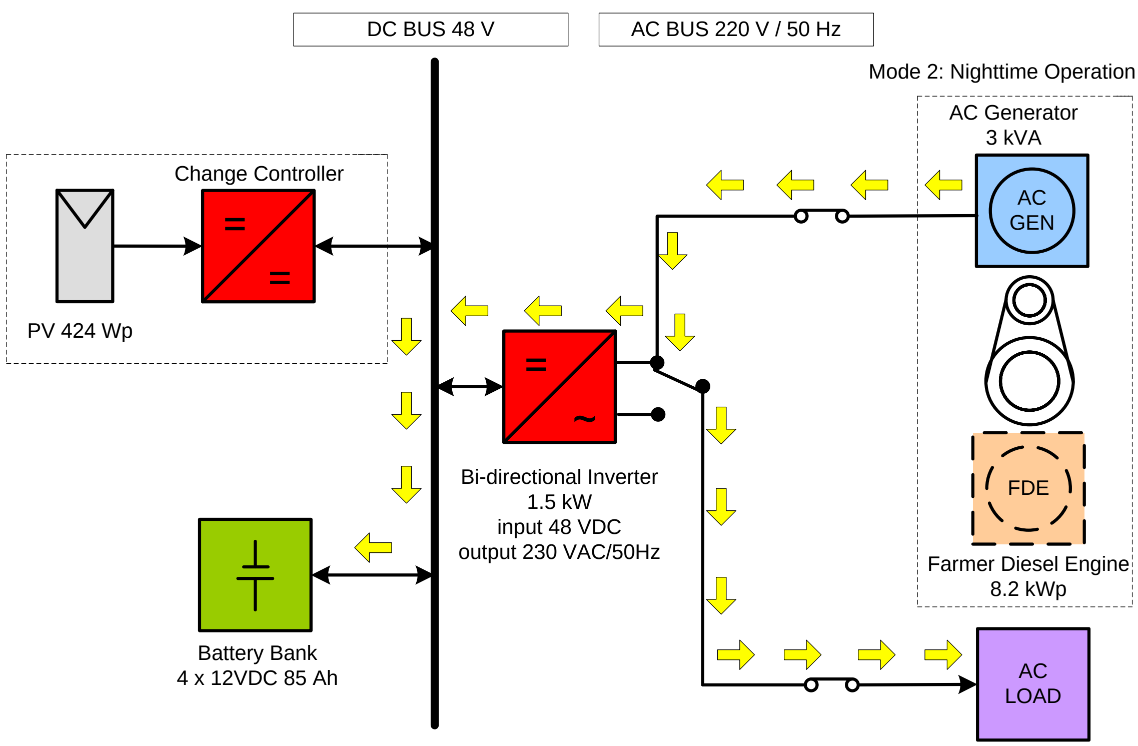

Figure 4-14: Mode 2: Nighttime Operation of PV-Bio FDE for HSHS

Mode1 & 2: All the time 24 hours exceeded energy from both PV generator and Farmer Diesel Engine driven AC Machine is backing up by batteries.

4.10 Summary

The problems of only using FDE to generate electricity supply to farmer households were identified at the beginning of this chapter. After reviewed the study of existing resources, traditional household power generation, culture, life style and electricity need of the farmers, an innovative thinking design concept of PV-Bio diesel from Farmer Diesel Engine for Hybrid Solar Home System [PV-Bio FDE for HSHS] came up to be the solution for electrification system for the farmers who owned FDE and have non-grid utility supply.

Ordinary Thai farmers usually live together in cluster. Each can have 3-5 family members. The selected farmer family to implement PV-Bio FDE for HSHS is in Phichit province as described in chapter 4.7.1 – 4.7.2

The conceptual design with design and select the system component criteria were present in chapter 4.7.3 -4.7.4.

This system generates AC 220 V/50 Hz and allows operation in 2 modes; 1. Mode 1: Daytime operation that power is generating from PV array and 2. Mode 2: Nighttime operation that power is received from store energy in battery for normal load demand and power from FDE while peak demand is incurred, while exceeded energy is backed up in battery bank.

Chapter 5 : PV-Bio FDE for HSHS Project Implementation & Results

5.1 Best Practiced System PV-Bio FDE for HSHS

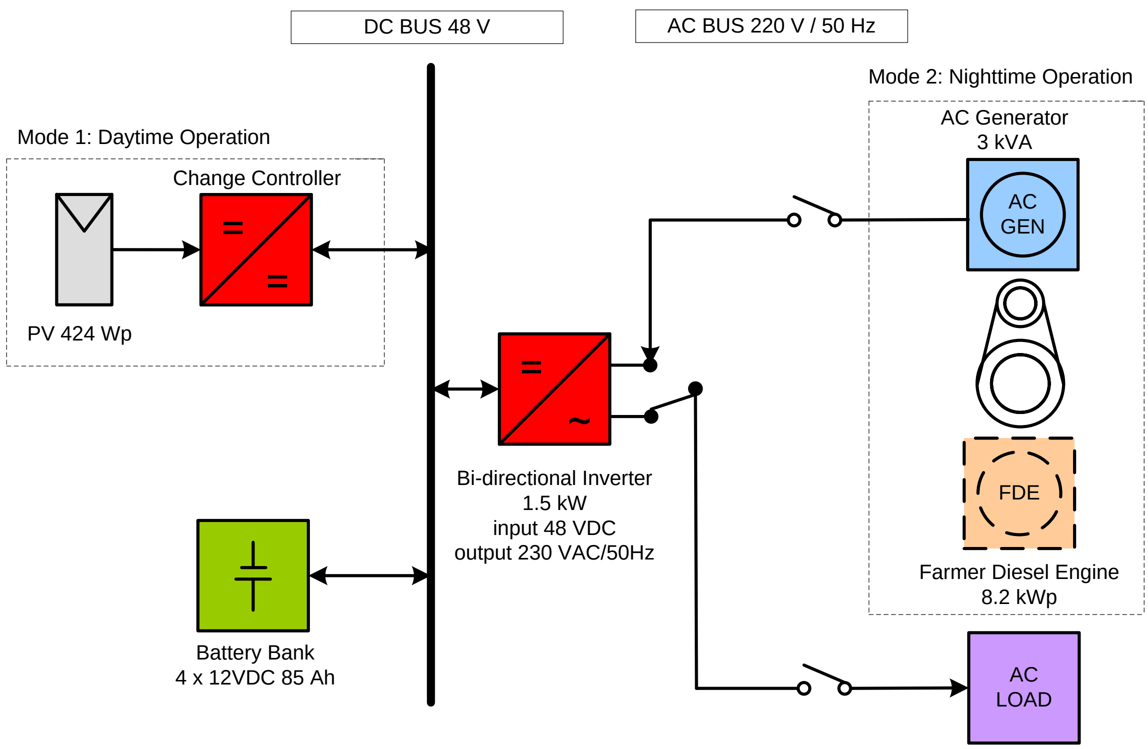

Figure 5-1: Best Practiced System of PV-Bio FDE for HSHS

5.2 Detailed Design Criteria and Key Components Selection

Under the supports of SERT and Leonics, the prototype of PV-Bio FDE for HSHS is developed to install in Farmer Household in Phichit. As mentioned in previous section, the design criteria of selecting the system components are to utilize as most as existing resources e.g. old PV-modules from failed PV – Battery charging project, existing farmer's AC Machine and FDE. The equipments that are needed to additionally provide are only Bi-directional inventor, batteries and charge controller.

Based on regular load analysis and system sizing procedure, the final chosen components to be integrated in "*Best Practiced System*" are in the following:

PV Array 424 W_p

PV – modules size used for installing in PV-Bio FDE for HSHS system in Phichit site is *"Single Crystalline Silicon Solar Cell"* type by manufacturer, SIEMENS with 53 W_p each. There are 2 strings in parallel with 4 modules in series in total output W_p = 424 W.

Battery Bank

Generally, there is no definite guide to select battery capacity and operating strategies for a hybrid system. Some of key factors that make up the design criteria (rule of thumb methods) basically depend on the nature of sources and loads, which are:

- Load energy consumption analysis
- Allowed depth of discharge (DOD)
- Number of days of autonomy
- System efficiencies or losses (e.g. battery, wiring, and power conversion)
- Operating temperature
- Allowed maximum battery weight
- Recommended charging rate (or battery charge acceptance rate)

In this work, chosen battery type is Lead-acid because of the lower initial cost and most common use in Thailand. Each battery has nominally DC rated voltage at 12 V_{dc} and capacity at 85 Ah. The batteries bank in series for this system is 4 units in total capacity of 4,080 Wh.

Bi – directional Inverter

By following selection criteria, the chosen inverter should be rated at least 20 % more than the maximum power of load to ensure its deliver power.

The Bi – directional Inverter which developing and manufacturing by Thai company, Leonics at rated power 1.5 kVA. This Bi – directional inverter has 2 mode operations: 1. to convert direct current from a battery bank to alternating current, 2. to convert alternating current generating from AC Machine driven by FDE to direct current. The nominal DC voltage is 48 V_{dc}, the AC voltage is 220 V_{ac} ± 1%, 50 Hz ± 0.1 % pure sine wave with total harmonic distortion less than 3%. The pure sine wave form is presented in Figure 5-2.

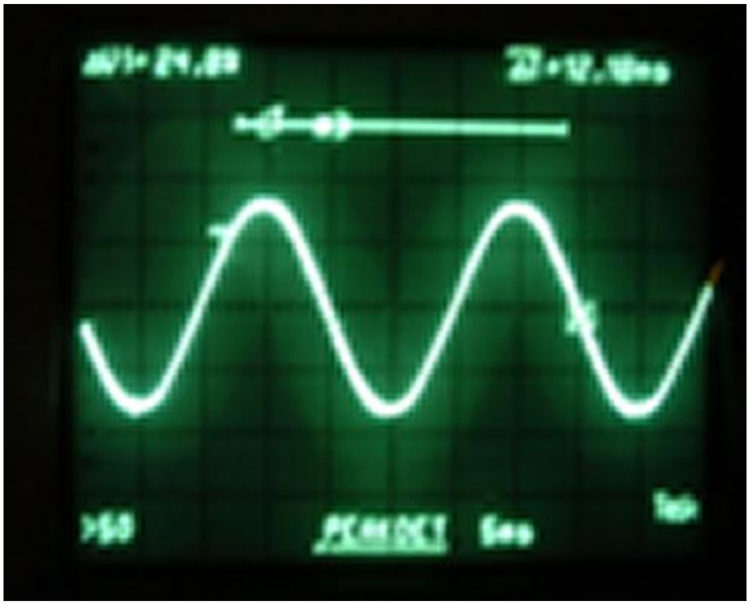

Figure 5-2: Pure sine wave form by Bi directional inverter

The charging DC current is at 18 A. The general protection features of this inverter are; overload / current, short circuit, over temperature, over current and under voltage. It has also LED indicator to monitor; load level, battery level, on/off status and alarm. The buzzer alarm system features will alert user in low battery, overload and short circuit case.

Figure 5-3: Photos of Best Practiced PV-Bio FDE for HSHS Taken in Farmer House, Phichit

Charge Controller

Charge controller is electronic device, which control the power output generating from PV array not to overcharge the battery. The used charge controller in this work is by Leonics model Solarcon. This charge controller has nominal input voltage at 48 V_{dc}. The maximum allowance current is 15 A.

- Advanced microprocessor control with a stage charging.
- Low loss PV back feed current protection.
- Reverse polarities protection for PV and battery.
- Overcharge protection.
- Lightning surge protection.
- Low battery shutdown with alarm.

AC Machine

The chosen farmer family has owned AC Machine at power rated 3kVA. Usually, they are coupling this AC Machine with FDE to generate electricity. In this work, AC Machine will be started when heavy load is connected to the system. AC Machine model S.S.D is single phase, synchronous type with 1,500 rpm, voltage 220 V, peak current at 11.3, and frequency 50 Hz.

Farmer Diesel Engine (FDE) [20]

FDE, which is used in the system in Phichit, has power rated at 8.2 kW (11 HP) with single piston engine. This existing FDE owned by farmer is normally used for farming, water pumping, transportation and coupling with AC Machine at night to generate electricity.

The general FDE specifications are described in the following:

- Diesel machine model RT 110 with 4 steps horizontal 1 piston.
- Heat veneration by water system.
- Maximum 11 HP/2,400 rpm.
- Fuel consumption 210 g – HP/ hour.
- Fuel capacity storage 11 liters.
- Total engine weight 109 kg.

A summary of the main system component dimensions are listed in Table 5-1:

Table 5-1: Summary of Main System Components

Component	Rating
8 x PV Array 53 Wp	total power rate 424 W
4 x Lead Acid Batteries 85 Ah, 12 V_{dc}	total 48 Vdc, capacity 340 Ah
1 x Bi-directional inverter	48 V_{dc} / 220 V_{ac}, 50Hz, rated 1.5 kVA
1 x Charge controller	48 V_{dc}, maximum charging current 15 A
1 x AC Machine	Induction type power rate 3kVA, 220 V_{ac}/50 Hz
1 x Farmer diesel engine	Power rate 11 HP (8.2 kW)

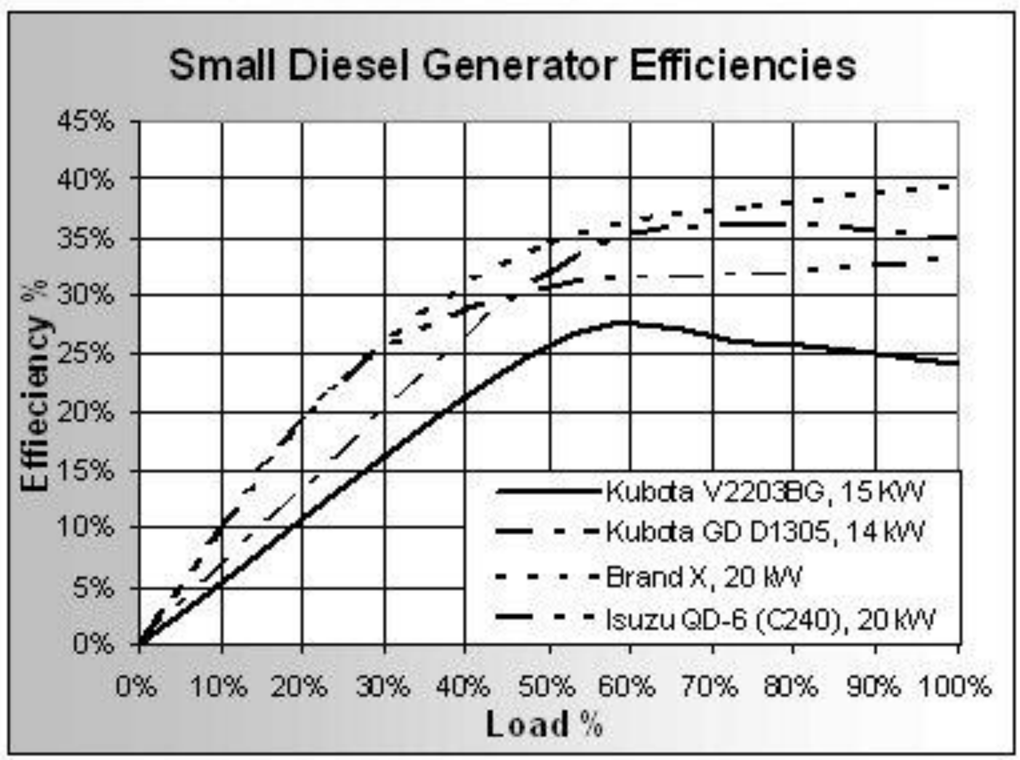

Figure 5-4: Diesel Generator Efficiencies

5.3 Data Measuring & Monitoring System

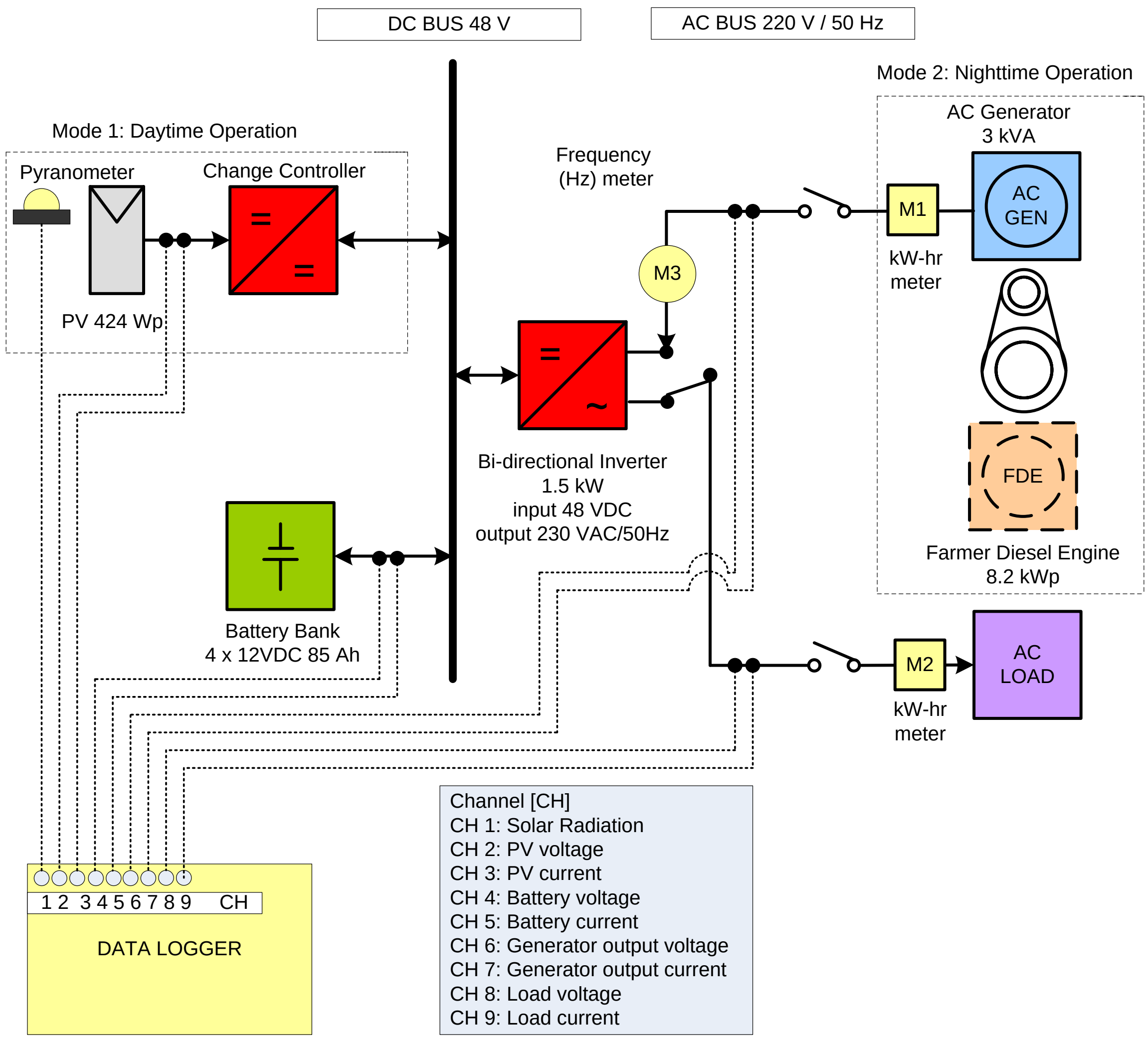

Figure 5-5: Monitoring System of PV-Bio FDE for HSHS

After the system has been installed, all data have to be monitored and later on analyzed. Figure 5-5 presents monitoring system diagram of PV-Bio FDE for HSHS. The data logger as data acquisition unit with acquisition software has been set to record all measured data by interval of 10 minutes during 6 months. All recorded data in data logger can be afterward downloaded to PC or Notebook through either USB or RS 232 communication port to be later analyzed.

The needs of analysis dictate the monitoring variables of the system. Table 5-2 shows the monitoring variables of this system.

Table 5-2: Monitoring Variable in System

CH	Monitoring Variable	Abbreviation	Unit
1	Solar Radiation	Gt	$W/m^2 \cdot day$
2	PV voltage	Vpv	Volt
3	PV current	Ipv	Amp
4	Battery voltage	Vbat	Volt
5	Battery current	Ibat	Amp
6	AC Machine output voltage	Vgen	Volt
7	AC Machine output current	Igen	Amp
8	Load voltage	Vuse	Volt
9	Load current	Iuse	Amp

Necessary measuring devices for monitoring this system are in the following:

- Data logger model squirrel 2020 supports 24 universal analog inputs for voltage, current or resistance measurement plus 2 high voltage , 4 pulse and 8 digital event/state inputs. Analog inputs can be used with thermistor, thermocouple and 2 wire PTD temperature sensor and 4 – 20 mA instrument. Internal memory is 16 Mb. Support USB and RS 232 Communication port [22].
- Pyranometer spectral response 305 – 2800 nm, angular response 2 % for angles > 70 degree, rangev1500 W/m^2, display resolution 1 W/m^2 environment -40 ^{o}F to 175 ^{o}F (-40 ^{o}C – 80 ^{o}C), temperature coefficient 6 % (-10 + 40 ^{o}C), cable length 15ft, 5m, dimension: diameter 2.375” , height 2.25” , total weight 240 g [21].
- Universal digital multimeter.
- Transducer DC voltage.
- Transducer DC current.
- Transducer AC voltage.
- Transducer AC current.
- Computer notebook.

5.4 Technical Data Analysis

Performance analysis used in this work refers to methodology from IEA PVPS Task 2 which defines variables in the following:

Array Yield

Energy, which generated by PV Array, is called *"Array Yield"*. It is calculated by equation

$$Y_a = E_a/P_o \qquad (5\text{-}1)$$

where:

Y_a = Array Yield [kWh/kWp]
E_a = Electricity energy generated by PV array [kWh]
P_o = Peak power of PV Array [kW_p]

Reference Yield

Electricity Energy generated by PV Array in theory is called *"Reference Yield"*. It is calculated by equation:

$$Yr = H_i/G_{STC} \qquad (5\text{-}2)$$

where:

Yr = Reference Yield [kWh/kWp]
Hi = Solar energy which impacting to area of PV array [kWh/m^2]
G_{STC} = Solar irradiation at PV standard testing condition, STC [kW/m^2]

Final Yield

Electricity Energy generated by PV Array in practical is called *"Final Yield"*. It is calculated by equation:

$$Y_f = E_{pv}/P_o \qquad (5\text{-}3)$$

where:

Y_f = Final Yield [hour/day]
E_{pv} = Energy generated by PV Array and delivered to load [kWh]

where:

$$E_{pv} = E_L / (1 + E_{BU}/E_a) \qquad (5\text{-}4)$$

where:

E_L = Electricity energy delivered to load in practical [kWh]
E_{BU} = Energy generated from secondary source, define to = 0 [kWh]

Performance Ratio

Performance Ratio (PR) of solar system is then calculated by equation

$$PR = Y_f / Y_r \quad (5\text{-}5)$$

PV Array Efficiency

PV Array Efficiency (η_A) is calculated by equation

$$\eta_A = E_a / (H_i \times A_A) \quad (5\text{ -}6)$$

where:

A_A = Area of PV array [m^2]

Total Efficiency

Total Efficiency (η_{PV}) is calculated by equation

$$\eta_{PV} = E_{PV} / (H_i \times A_A) \quad (5\text{-}7)$$

5.4.1 6 Months Solar Radiation

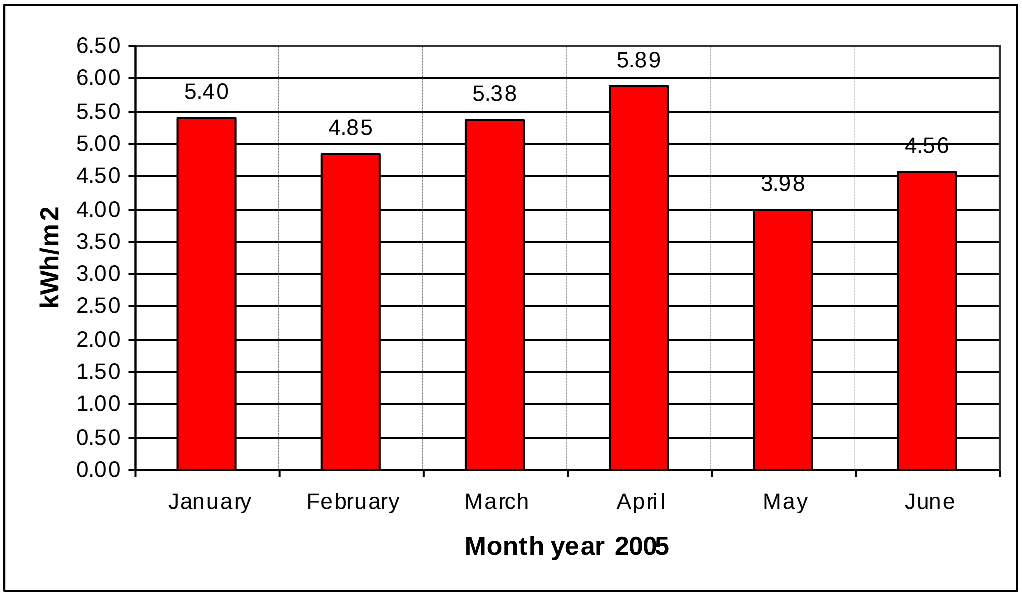

Figure 5-6: 6 Months Solar Radiation in Phichit

The figure 5-6 represents the potential of solar radiation in Phichit, Thailand during January to June 2005. The range of solar radiation is quite high in between 3.98 – 5.89 kWh/m^2·day.

5.4.2 Load Demand Profile

The average 6 months (January – June 2005) daily load demand profile by interval of this farmer is presented in Figure 5-7. Average electricity consumption is approximately 3 kWh/day. The demand pattern represents that farmer family use electricity only night time from 17:00 – 18:00 in the evening to 6:00 – 7:00 in the morning. Peak demand is regularly started during 19:00 – 20:00 when the farmer starts using rice cooker.

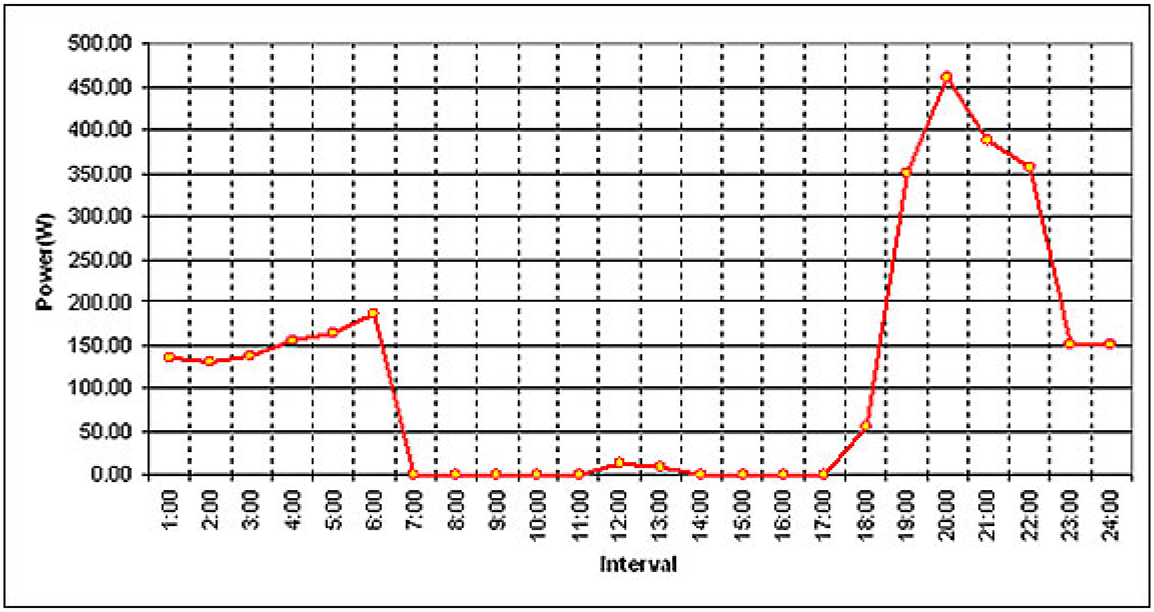

Figure 5-7: Average 6 months Load Curve Characteristics

Table 5-3 presents the appliances use in Phichit farmer households. This family joined also 120 W, SHS program. Since they have had electricity, they do need to have more electric devices e.g. rice cooker to serve their comfort. This is study case to confirm that the electricity demand will be increased after non-electrified people have an access to electricity.

Table 5-3: Electric Appliances with Rate Power

Appliance	Units	Power (W)/unit	Power Total (w)
Lump	10	15	150
TV 21″	1	80	80
TV 14″	1	60	60
Fan	3	180	180
CD player	1	80	80
Rice cooker	1	600	600
Other			100
		TOTAL	1,250

5.4.3 Solar Radiation with Generated Power by PV-Modules

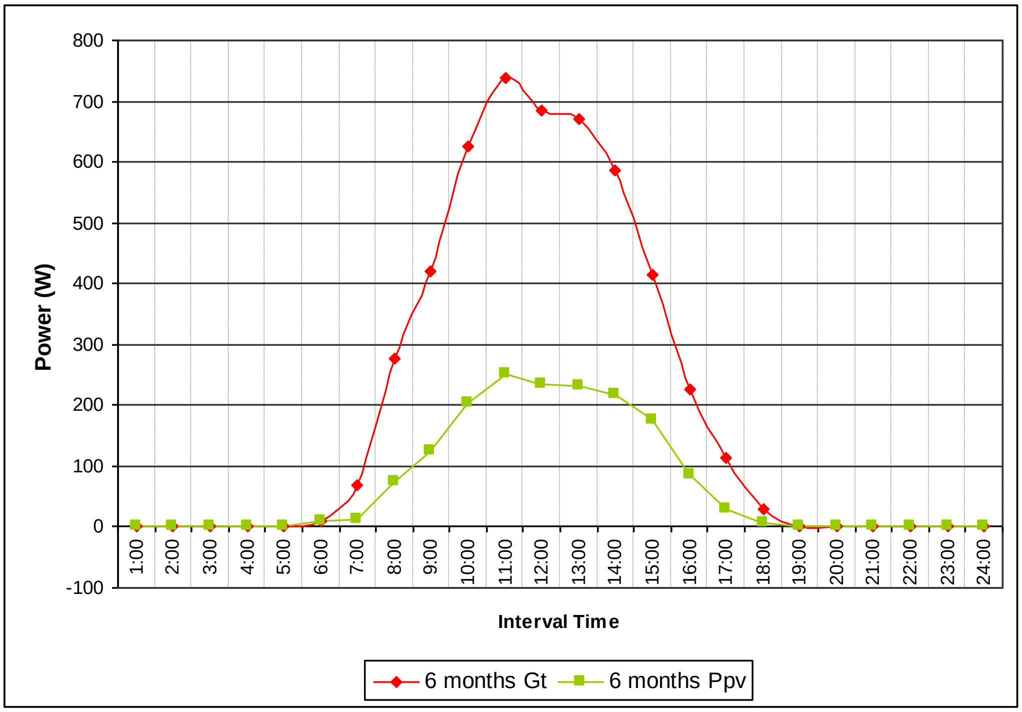

Figure 5-8: Average Solar Radiation versus Power Generated by PV-Modules

Average 6 months of solar radiation and power generated by PV- modules are presented in Figure 5-8. Peak solar radiation is at 739 W while PV-module can generate DC power at 252 W.

5.4.4 Power Generated by PV-Modules (W), Battery and AC Machine

The results of power generated by PV- modules and AC Machine in correlation with battery are shown in Figure 5-9 and 5-10. The chosen 2 cases are presented to distinguish the day that AC Machine is on and off operation.

Sample power curve of the day which AC Machine is not starting is shown in Figure 5-9. On daytime power, which is generated by PV is charged in battery bank, while in the nighttime power is discharged from battery and delivered to regular load use.

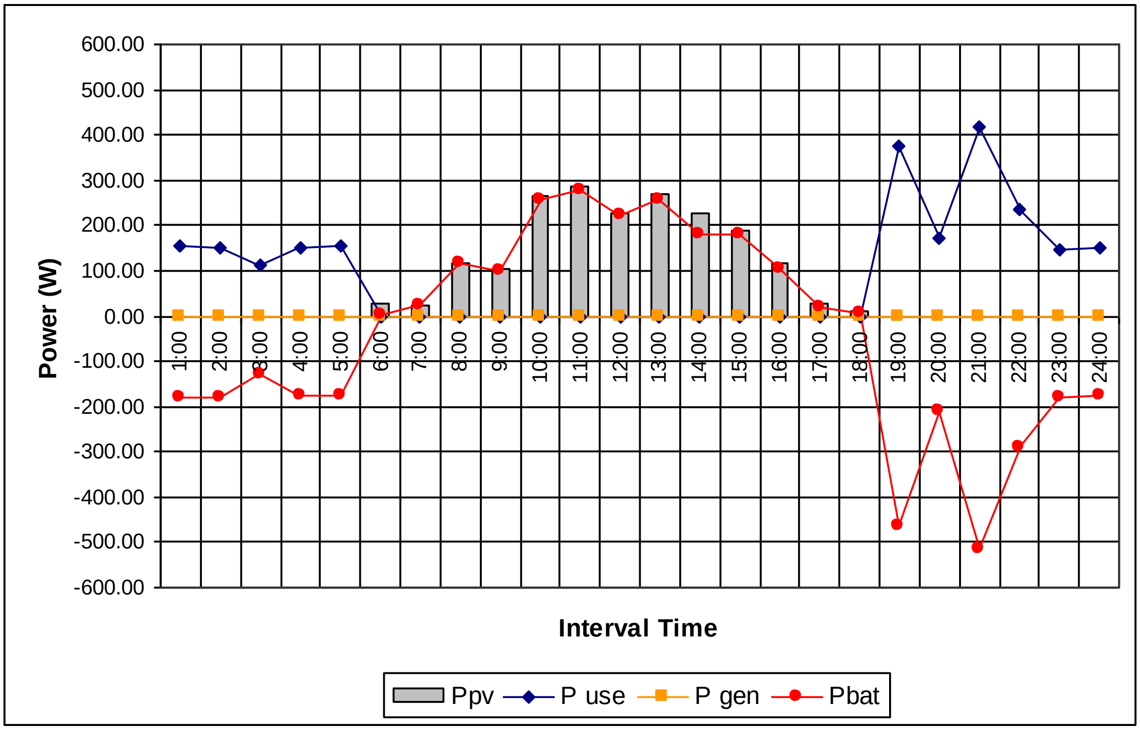

Figure 5-9: Power Curve on the Day (which is not starting AC Machine)

Once farmer use all heavy load at the same time and discharge power from battery is not sufficient, farmer has to coupling Farmer Diesel Engine 11 HP with AC Machine using belt and start to generate power supply the peak load at approximately 800 Watt. As can be seen in Figure 5-10, AC Machine is started to supply the peak load at 19:00 while excess power is delivered to store in battery bank. In this mode, once Farmer Diesel Engine starts and drives AC Machine in certain speed, AC Machine (Synchronous Generator) will generate electricity with acceptable range of Bi-directional Inverter. As designed specification of Bi-directional Inverter is in the range of 45Hz-55Hz, the speed of Farmer Diesel Engine is controlled manually by the accelerator pedal.

The combination of solar radiation, power generated by PV, power used at load, power generated by Farmer Diesel Engine, and left power charged to battery, as can be seen, during day time from 7:00 to 17:00 since, there is sunlight, PV generates electricity and is charged by charging controller to battery. In night time, when heavy duty load like rice cooker is needed is 20:00, Farmer Diesel Engine coupling with synchronous generator is then started to supply load.

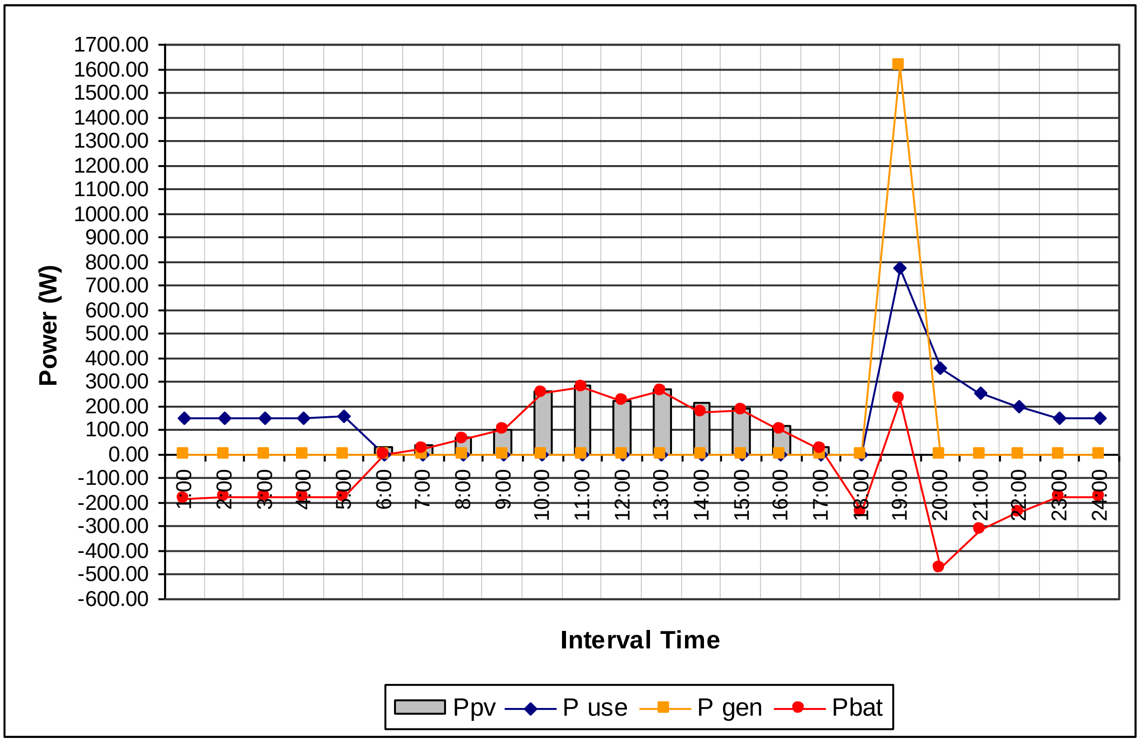

Figure 5-10: Power Curve on the Day (which is starting AC Machine)

5.4.5 Combine All Curves

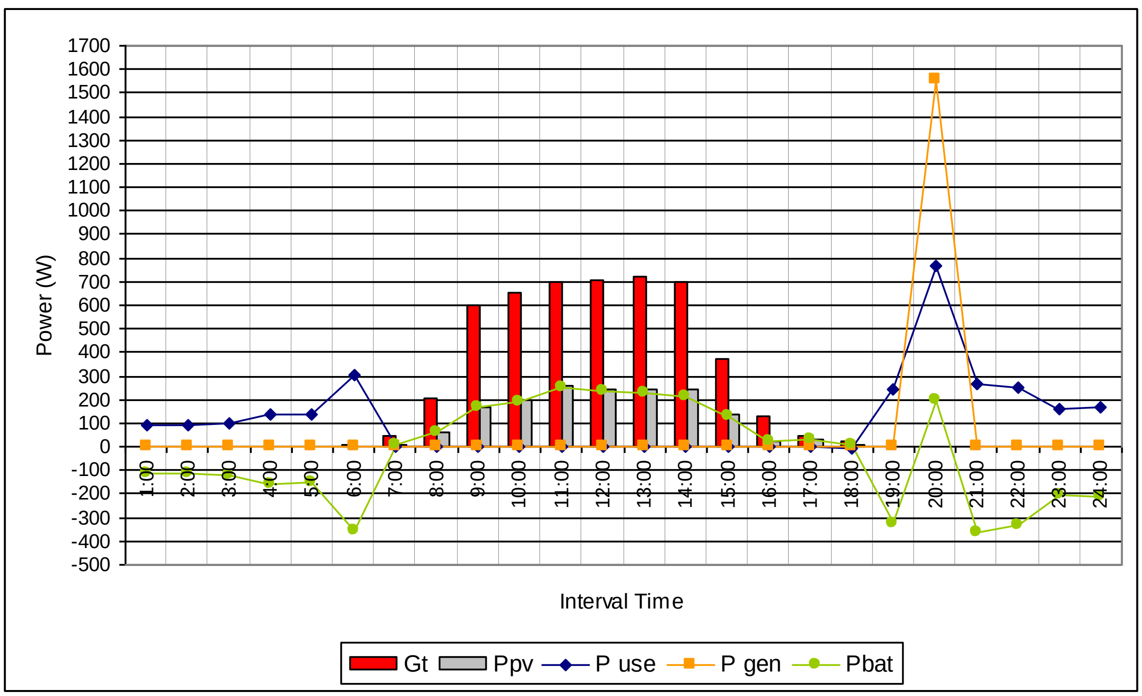

Figure 5-11: Combine All Curves

The monitored data, solar radiation (G_t), power generated by PV (P_{pv}), power use by load (P_{use}), power generated by Farmer Diesel Engine coupling with AC Machine (P_{gen}) and power charge/discharge from battery (P_{bat}) are combined in Figure 5-11.

5.5 Analysis & Evaluation System Performance

Table 5-4 presents the system performance during 6 months; the 6 months average solar radiation is rather potential at 5.01 kWh/m^{2,} the energy generate from PV and AC Machine and the energy supply to the load can be seen in kWh.

The 6 months average PR of the whole system is 70.60%. The average solar fraction of the system is 69.64% and Final Yield is 3.54 hours/day. This potential of the system is comparably high to the potential range of PV hybrid system. One reason is the high uniformity of the irradiation profile throughout the year.

Table 5-4: System Performance factors

Month	Radiation (kWh/m2)	PV (kWh)	Load (kWh)	Gen. (kWh)	PR	Solar fraction	% eff. Inverter	% eff. PV	Final Yield
Jan	5.40	54.28	75.07	26.07	71.45	72.31	82.54	7.28	3.86
Feb	4.85	44.67	64.71	23.70	73.43	69.03	83.24	6.06	3.56
Mar	5.38	57.18	65.70	17.78	70.88	87.03	76.21	5.86	3.81
Apr	5.89	55.00	74.10	23.70	69.12	74.22	76.75	5.88	4.07
May	3.98	36.00	67.00	34.37	65.53	53.73	83.20	6.55	2.61
Jun	4.56	44.31	72.00	30.81	73.22	61.54	80.39	6.33	3.34
Average	5.01	48.57	69.76	26.07	70.60	69.64	80.39	6.33	3.54

Table 5-5 presents the frequent start of AC Machine which coupling FDE. The average started frequency of AC Machine is 22 times/month. The average monthly AC Machine operating hours is 15.79 hours/month represented that each of AC Machine operation time per start is only 41 minutes. It reflects to the average minimal use of Bio fuel use at only 39.35 liters/month.

Table 5-5: AC Machine Start/ Stop, Operation Hours and Fuel Consumption

Month	Gen.Start / month (times)	Gen. Operating (hours)	Fuel Used (ltr/month)
Jan	22.00	16.50	40.43
Feb	20.00	13.50	34.02
Mar	15.00	10.58	25.88
Apr	20.00	13.27	33.70
May	29.00	21.75	54.59
Jun	26.00	19.15	47.50
Average	22.00	15.79	39.35

Figure 5-12 illustrates more view of monthly performance ratio versus final yield of the system.

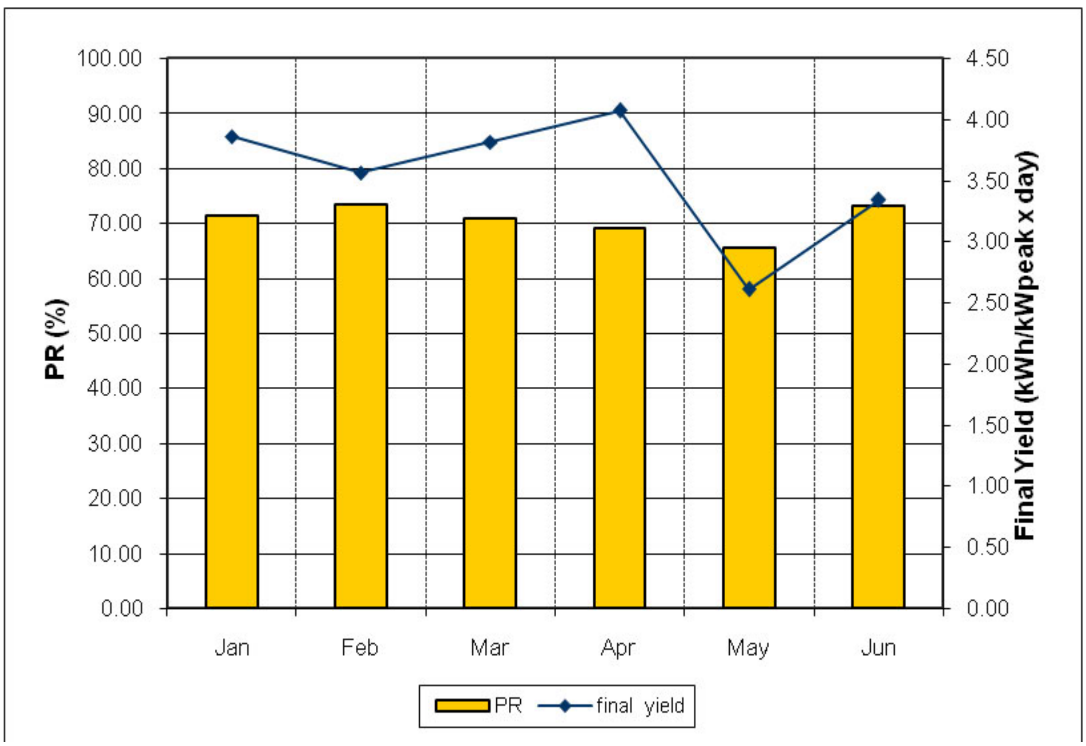

Figure 5-12: Monthly Performance Ration versus Final Yield

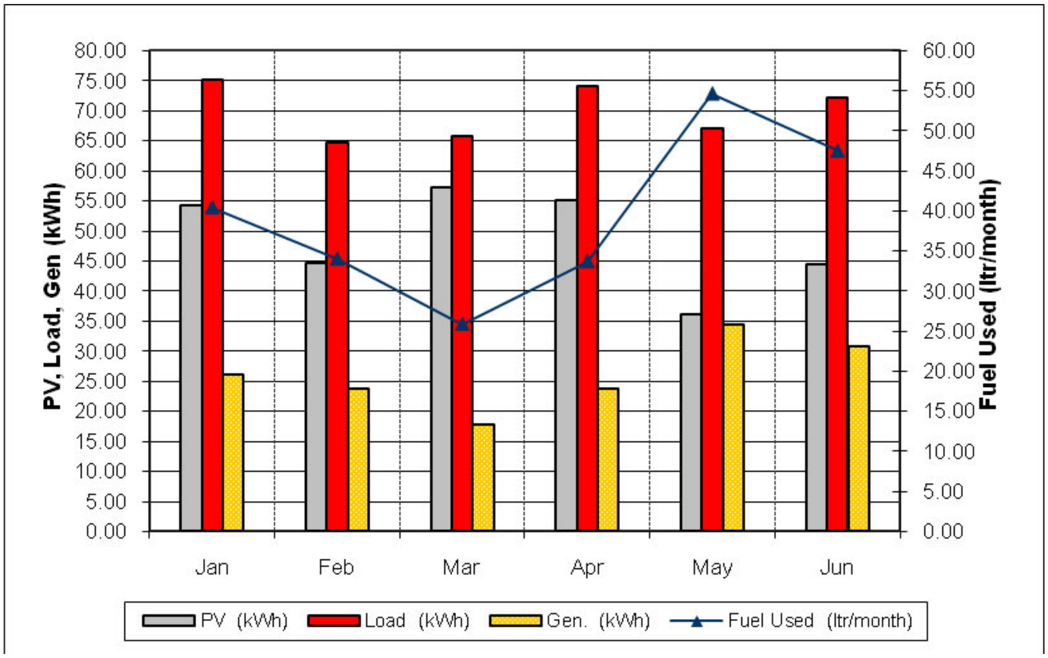

Figure 5-13: Monthly PV, Load, and AC Machine Energy versus Bio Diesel Fuel Used

Figure 5-13 presents the energy balance of the system. The monthly average energy generated by PV is 48.57 kWh; the monthly average energy supplied by the AC Machine is 26.07 kWh that reflect to monthly average of net energy use by load at 69.76 kWh. The monthly average fuel use is also represented in graph in according to energy generated by AC Machine.

5.6 Summary

The best practiced system of PV-Bio FDE for HSHS with selected components were concluded in chapter 5.2 which are in the following table:

Component	Rating	Resource
8 x PV Array 53 Wp	total power rate 424 W	SHS Existing
4 x Lead Acid Batteries 85 Ah, 12 V_{dc}	total 48 Vdc, capacity 340 Ah	Buy new
1 x Bi-directional inverter	48 V_{dc} / 220 V_{ac}, 50Hz, rated 1.5 kVA	Buy new
1 x Charge controller	48 V_{dc}, maximum charging current 15 A	Buy new
1 x AC Machine	power rate 3kVA, 220 V_{ac}/50 Hz	Existing
1 x Farmer diesel engine	Power rate 11 HP (8.2 kW)	Existing

Necessary measuring and monitoring devices were set to monitor and record variables of this system in the period of 6 months from January 2005 to June 2005. The monitored data are solar radiation (G_t), PV voltage (V_{pv}), PV current (I_{pv}), battery voltage (V_{bat}), battery current (I_{bat}), AC Machine output voltage (V_{gen}), AC Machine output current (I_{gen}), load use voltage (V_{use}) and load use current (I_{use}). The system performances during 6 months were determined in various illustrative graphs and tables.

Some significant parameters, which indicate performance of this system, are concluded as follows:

- Solar radiation in Phichit, Thailand during January – June 2005 is rather high potential in the range of 3.98 – 5.89 kWh/m^2·day.
- Average electricity consumption is about 3 kWh/day. As can be seen in load profile of farmer family. Peak demand is regularly incurred during 19:00 – 20:00. In the day peak demand is higher than energy supply by battery, FDE then has to be coupling with AC Machine and started.
- The 6 months average PR of the whole system is rather good at 70.60%. It can be described that even most system components were old and low efficiency such as used PV Array and AC Machine, but when they are integrated in hybrid system the PR are improved.

Battery Management: In this system, the battery with capacity 4 kWh cannot be fully charged with short running times of the diesel which is start manually in operation period of 40 – 60 minutes per start for mainly peak load supply purpose, the battery management with a full charge during daytime by PV can not be done because 424 W PV Arrays can generate energy only approximately 1.4-1.8 kWh/day. To manage battery to fully charge can be done by creating manually schedule to run the diesel to fully charge battery once battery level below DOD limit to maintain battery longer lifetime use.

Chapter 6 : Techno – Economical Analysis

The previous chapter has explained on system performance analysis of PV-Bio FDE for HSHS. In this chapter will describe the economical analysis of this system in order to compare with other electrifications e.g. PV, a local diesel AC Machine, and SHS project. Whatever technical solution is chosen, the benefits should be determined. The angle views of benefits consideration should not be described only technical performance of the system but can also address social, economics and environmental improvement induced through its provision of electrification service.

In economic evaluation, usual parameters we consider are in the following:

- The initial costs (the initial capital cost)
- The operation and maintenance cost (O&M)
- The Life-cycle cost

6.1 Initial Costs and O &M Costs

6.1.1 Initial Costs

The initial costs in PV-Bio FDE for HSHS are the costs incurred through purchasing system components and hiring labors to install the system. Generally all components, which combine in the system, have to be calculated. In this work, it is assumed that recycle PV-modules transferred from other failed projects (SHS, PV battery charging, PV –pumping and etc.) and Farmer Diesel Engine which 70 %– 80 % of Thai farmer family owned are free of charge components in initial costs.

Therefore, the definition of this economic analysis model will be under condition:

- PV- modules will not be taken into account in initial costs calculation.
- Farmer Diesel Engine (FDE) will not also be used in initial cost calculation.

Only the components will be considered in initial costs in this economic analysis modeling are in the following:

- AC Machine
- Batteries
- Charge Controller
- Bi-directional inverter
- Plugs, connectors, switches and wires
- Labor costs for installation

6.1.2 Operation & Maintenance (O & M) Costs

Operation & Maintenance (O&M) costs incurred after installation to operate and maintenance the system for a certain number of years, so called “project life”. The project life is an important parameter, which helps to benchmark different life cycle costs or net present value costs for different designs. O&M costs generally include expense for fuel, lubrications, maintenance, overhaul, wears and components replacement.

6.2 Life Cycle Costs (LCC) Assessment of System

6.2.1 Step for Calculation

In this work, the *Life Cycle Cost* (*LCC)* method is used to determine economic concerns. The *LCC* converts all future costs and payments as its present values. The *LCC* analysis can be set up for virtually any type of system. Following SIEMENS hybrid sizing and economic comparison workbook, the steps of *LCC* calculation are concluded in the following [16]:

- To calculate the initial capital cost.
- To calculate the annual recurring fuel cost, then multiply by the factor that accounts for the discount rate (*d*), fuel escalation rate (*FE*) and period of analysis (*N*).
- Calculate the annual recurring maintenance costs, and then multiply by the factor that accounts the discount rate (*d*), Excess inflation rate (*i*) and period of analysis in year (*N*).
- Determine the schedule for each non-recurring items with costs and multiply the costs by a factor to account for the discount rate (*d*), Excess inflation rate (*i*) and the replacement year (R_n).
- To summarize each non-recurring items costs to total non-recurring costs.
- The total LCC (ALCC) is calculated by the sum of ; 1 initial capital costs, 2 annual recurring fuel cost, 3 annual recurring maintenance costs and 4 total non-recurring costs.
- The electricity *cost (€/kWh)* is determined by total LCC (ALCC) dividing into the total of electricity energy (kWh) produced.

6.2.2 Calculation Formula [16, 17]

Ann Recur Fuel Costs = $AnnFuelCost \times \left\{ \left(\frac{1+FE}{d-FE} \right) \times \left[1 - \left(\frac{1+FE}{1+d} \right)^{N} \right] \right\}$

where:

Ann Recur Fuel Costs	=	Annual Recurring Fuel Costs
Ann Fuel Cost	=	Annual Fuel Cost
FE	=	Fuel Escalation Rate
d	=	Discount Rate
N	=	Period of Analysis

Ann Recurr Maint Costs = $AnnMaintCost \times \left\{ \left(\frac{1+i}{d-i} \right) \times \left[1 - \left(\frac{1+i}{1+d} \right)^{N} \right] \right\}$

where:

Ann Recurr Maint Costs	=	Annual Recurring Maintenance Costs
Ann Maint Cost	=	Annual Maintenance Cost
i	=	Excess Inflation Rate
d	=	Discount Rate
N	=	Period of Analysis .

Non-Recurr Costs = $\sum \left\{ ItemCost \times \left[\left(\frac{1+i}{1+d} \right)^{Rn} \right] \right\}$

where:

Non Recurr Costs	=	Non Recurring Costs
Item Cost	=	Non recurring in the present costs
R_n	=	Replacement year

ALCC = $\frac{CapitalCost + LCC\,FuelCost + LCC\,MaintCost + LCC\,ReplCost}{N \times 365 \times E}$

ALCC	=	Total Life Cycle Cost Per Year
LCC	=	Life Cycle Cost
N	=	Period of Analysis
E	=	Total of Electricity energy (kWh) produced

6.2.3 Parameters and Calculation Results [13]

Economic Factors

The calculation of life-cycle cost requires values to be known for the following items:

- *Period of analysis* (N): The lifetime of the longest-lived system under comparison. In this LCC analysis, period of analysis (N) of 20 years is used in calculation.
- Excess inflation rate (i): The rate of price increase of a component above or below. In this analysis, inflation rate (i) is 5%.
- *Discount rate (d)*: The rate (relative to general inflation) at which money would increase in value if invested (typically 8-12%). The value 10% is selected to be an input in this LCC calculation.
- Fuel Escalation rate (FE): This is the factor to describe that fuel price rate increase over time and logistic expenses to remote area. In this work, fuel escalation rate of 7% is applied in calculation.
- *Capital cost*: The total initial cost of buying and installing the system.
- *Operation and maintenance*: The amount spent each year in keeping the system operational.
- *Fuel costs*: The annual fuel bill.
- *Replacement costs*: The cost of replacing each component at the end of its lifetime.

Table 6-1: Part Economic Factors LCC Analysis (Regardless FDE and PV Array) and (Regard FDE and PV Array) [17]

Life Cycle Cost Analysis		
Exchange Rate 1€ =	49 baht	15/01/08
System Description	**Location**	**Average Energy Requirement**
Hybrid System	Phichit / Thailand	2.87 kWh/day
Economic Factors		
Item	**Value**	**NPV Factor**
LCC Period (years)	20	
Discount Rate (d)	10%	
Fuel Escalation (FE)	7%	15.15
Inflation Rate (i)	5%	12.72

Table 6-2: Part Initial Capital Costs in LCC Analysis (Regardless FDE and PV Array) [17]

Initial Capital Costs			
Item	**Quantity**	**Cost**	**Extended Cost**
FDE 11 HP	1	0.00 €	0.00 €
AC Machine 3 kW	1	510.20 €	510.20 €
Charge Controller	1	71.43 €	71.43 €
PV Array	8	0.00 €	0.00 €
Battery Bank	4	61.22 €	244.90 €
Inverter 1.5 kVA	1.0	600.00 €	600.00 €
Building	0	0.00 €	0.00 €
Installation	1	204.08 €	204.08 €
			0.00 €
		Total Initial Capital	1,630.61 €

Table 6-3: Part Initial Capital Costs in LCC Analysis (Regard FDE and PV Array) [17]

Initial Capital Costs			
Item	**Quantity**	**Cost**	**Extended Cost**
FDE 11 HP	1	640.00 €	640.00 €
AC Machine 3 kW	1	510.20 €	510.20 €
Charge Controller	1	71.43 €	71.43 €
PV Array	8	190.80 €	1,526.40 €
Battery Bank	4	61.22 €	244.90 €
Inverter 1.5 kVA	1.0	600.00 €	600.00 €
Building	0	0.00 €	0.00 €
Installation	1	204.08 €	204.08 €
			0.00 €
		Total Initial Capital	3,797.01 €

Table 6-4: Part O & M Costs: Recurring Maintenance Costs (Regardless FDE and PV Array) [17]

O & M Costs ***Recurring Maintenance Costs***				
Fuel	**Annual Hours**	**Liters/hr**	**Cost/liter**	**Annual Cost**
Fuel use only for electricity	200	2.50	0.41 €	204.08 €
Maintenance	**Period (hours)**	**Frequency / year**	**Cost/Event**	**Extended Cost**
Oil Change		2.0	8.16 €	16.33 €
Overhaul		0.1	204.08 €	20.41 €
General		1.0	40.82 €	40.82 €
				0.00 €
			Total Recurring Maintenance Costs	77.55 €

Table 6-5: Part O & M Costs: Recurring Maintenance Costs (Regard FDE and PV Array) [17]

O & M Costs ***Recurring Maintenance Costs***				
Fuel	**Annual Hours**	**Liters/hr**	**Cost/liter**	**Annual Cost**
Fuel use only for electricity	200	2.50	0.41 €	204.08 €
Maintenance	**Period (hours)**	**Frequency / year**	**Cost/Event**	**Extended Cost**
Oil Change		2.0	8.16 €	16.33 €
Overhaul		0.1	204.08 €	20.41 €
General		1.0	40.82 €	40.82 €
				0.00 €
			Total Recurring Maintenance Costs	77.55 €

Table 6-6: Part O & M Costs: Non-Recurring Items and Its Costs (Regardless FDE and PV Array) [17]

O & M Costs ***Non-Recurring Items and its costs***				
Item	**Cost (present)**	**Year**	**NPV Factor**	**NPV Cost**
		1	0.955	0.00 €
Battery Repl + 10% labor	269.39 €	2	0.911	245.45 €
		3	0.870	0.00 €
Battery Repl + 10% labor	269.39 €	4	0.830	223.65 €
Charge Controller + 10%	78.57 €	5	0.792	62.27 €
Battery Repl + 10% labor	269.39 €	6	0.756	203.78 €
		7	0.722	0.00 €
Battery Repl + 10% labor	269.39 €	8	0.689	185.67 €
		9	0.658	0.00 €
Battery Repl + Inverter+	1,007.96 €	10	0.628	633.01 €
Charge Con + 10% labor		11	0.599	0.00 €
Battery Repl + 10% labor	269.39 €	12	0.572	154.15 €
		13	0.546	0.00 €
Battery Repl + 10% labor	269.39 €	14	0.521	140.45 €
Charge Controller + 10%	78.57 €	15	0.498	39.10 €
Battery Repl + 10% labor	269.39 €	16	0.475	127.97 €
		17	0.453	0.00 €
Battery Repl + 10% labor	269.39 €	18	0.433	116.60 €
		19	0.413	0.00 €
		20	0.394	0.00 €
			Total Non-Recurring Costs	2,132.11 €

Table 6-7: Part O & M Costs: Non-Recurring Items and Its Costs (Regard FDE and PV Array) [17]

O & M Costs ***Non-Recurring Items and its costs***				
Item	**Cost (present)**	**Year**	**NPV Factor**	**NPV Cost**
		1	0.955	0.00 €
Battery Repl + 10% labor	269.39 €	2	0.911	245.45 €
		3	0.870	0.00 €
Battery Repl + 10% labor	269.39 €	4	0.830	223.65 €
Charge Controller + 10%	78.57 €	5	0.792	62.27 €
Battery Repl + 10% labor	269.39 €	6	0.756	203.78 €
		7	0.722	0.00 €
Battery Repl + 10% labor	269.39 €	8	0.689	185.67 €
		9	0.658	0.00 €
Battery Repl + Inverter+	1,007.96 €	10	0.628	633.01 €
Charge Con + 10% labor		11	0.599	0.00 €
Battery Repl + 10% labor	269.39 €	12	0.572	154.15 €
		13	0.546	0.00 €
Battery Repl + 10% labor	269.39 €	14	0.521	140.45 €
Charge Controller + 10%	78.57 €	15	0.498	39.10 €
Battery Repl + 10% labor	269.39 €	16	0.475	127.97 €
		17	0.453	0.00 €
Battery Repl + 10% labor	269.39 €	18	0.433	116.60 €
		19	0.413	0.00 €
		20	0.394	0.00 €
			Total Non-Recurring Costs	2,132.11 €

Table 6-8: Cost Summary (Regardless FDE and PV Array) [17]

Cost Summary				
list of all cost		**Annual Cost**	**NPV Factor**	**Life Cycle Cost**
Initial Capital Costs	1,630.61 €			1,630.61 €
All Non-Recurring Costs	2,132.11 €			2,132.11 €
Annual recurring Fuel costs		204.08 €	15.15	3,092.05 €
Annual recurring maintenance costs		77.55 €	12.72	986.27 €
			Total LCC Cost (ALCC)	7,841.05 €
			Total Energy (kwh)	20,984
			Electricity Cost / kWh (NPV)	0.37 €
			Cost / kWh (NPV) in baht	18.68

Table 6-9: Cost Summary (Regard FDE and PV Array) [17]

Cost Summary				
list of all cost		**Annual Cost**	**NPV Factor**	**Life Cycle Cost**
Initial Capital Costs	3,797.01 €			3,797.01 €
All Non-Recurring Costs	2,132.11 €			2,132.11 €
Annual recurring Fuel costs		204.08 €	15.15	3,092.05 €
Annual recurring maintenance costs		77.55 €	12.72	986.27 €
			Total LCC Cost (ALCC)	10,007.45 €
			Total Energy (kwh)	20,984
			Electricity Cost / kWh (NPV)	0.48 €
			Cost / kWh (NPV) in baht	23.85

Table 6-10: Electricity cost of the system with/without regarding FDE & PV Array costs

List of cost	**Regard FDE & PV Array**	**Regardless FDE & PV Array cost**
Initial Capital Costs	3,776.40 €	1,630.61 €
LCC Replacement Costs	2,132.11 €	2,132.11 €
LCC Fuel costs	3,092.05 €	3,092.05 €
LCC maintenance costs	986.27 €	986.27 €
Total LCC Cost (ALCC)	10,007.45 €	7,841.05 €
Total Energy (kwh)	20,984	20,984
Electricity Cost / kWh (NPV) in Euro	0.48 €	0.37 €
Electricity Cost / kWh (NPV) in baht	23.85	18.68

As mentioned in previous section, in this work PV- Array and Farmer Diesel Engine (FDE) are not be taken into account in initial costs calculation because it is assumed that those two items are existing at farmer family who joined 120W Solar Home System.

As can be seen in Table 6-10, electricity cost when regardless FDE & PV Array costs is 0.37 €/kWh. When FDE & PV Array costs are included, it actually results to higher electricity cost to 0.48 €/kWh.

6.3 Environmental Evaluation & Assessment

The conversion factors that use to calculate in environmental evaluation are guided in Table 6-11.

Table 6-11: Fuel Conversion Factors [23, 25,28]

Fuel	Usual Units	Conversion Factor	Conversion Factor units
Electricity	kWh	1	kWh/kWh
Gas Oil	liters	10.6	kWh/liter
Fuel Oil	liters	11.4	kWh/liter
Propane	kg	13.89	kWh/kg
Butane	kg	13.69	kWh/kg
Dry steam coal	tones	8,500	kWh/tone
Anthracite	tones	8,236	kWh/tone
Coke	tones	7,750	kWh/tone

By implementing the PV-Bio FDE for HSHS systems, it can be compared that it can save energy equivalent to other source to generate the same amount of electricity in one year (Total Energy 20,984 kWh per year). The results are presented in Table 6-12.

Table 6-12: Savings Fuel Consumption, Electricity and Coal Assessment

Fuel type	Saving quantity per year	Unit
1. Fuel Oil	1,840.70	l / year
2. Electricity	20,985	kWh / year
3. Coal	2.47	tones / year
4. Natural gas	1,979.62	liters/ year
5. propane	1,510.8	kg / year
6. Butane	1,532.87	kg / year

Burning fossil fuels such as coal and oil produces emissions of greenhouse and acid gas which result in global warming and acid rain respectively. These air emissions in Thailand have risen sharply in the past decade, a direct result of the increased use of coal and natural gas in the thermal-electric electricity generation in the country.

Regarding this PV diesel hybrid system, produced electricity has a far smaller impact on the environment. During it normal operation, PV cell use no fuel other than sunlight while bio diesel would be consumed just only sometimes.

Comparing electricity generation from fossil fuel with this hybrid system, hybrid system could reduce the air pollution as shown in the following.

In order to calculate the carbon dioxide (CO_2), Nitrogen oxide (NO_x) and sulphur dioxide (SO_2) emissions associated with the energy use, simply multiply primary energy use by fuel type by the appropriate factor is guided in Table 6-13.

Table 6-13: CO_2, NO_x and SO_2 Conversion Factors [23, 25]

Type power Plant	CO_2	NO_x	SO_2	unit
Coal	300	200	250	g / kWh
Oil	250	0.36	1.6	g / kWh
Jatropha Oil	250	0.36	0	g / kWh
Natural gas	190	0.202	0.011	g / kWh
Fossil fuel electricity	430	1.134	3.14	g / kWh

Refer to forecasting annual electricity generated by PV –Bio FDE for HSHS of approximately 20,984 kWh/year, it is possible to represent the emission reduction of CO_2, NO_x and SO_2.

Table 6-14: CO_2, NO_x and SO_2 Emission Reduction

Type power Plant	CO_2 reduction per year	NO_x reduction per year	SO_2 reduction per year	unit
Coal	6,295.2	4,196.8	5,246	kg / year
Oil	5,246	7.56	33.57	kg / year
Jatropha Oil	5,246	7.56	0	kg / year
Natural gas	3,986.96	4.24	0.23	kg / year
Fossil fuel	9,023.12	23.8	65.89	kg / year

6.4 Social – Economical - Environmental Benefits

- Villagers supported the fund from government in PV Solar Home System Project could apply this system to the hybrid system. As a result, people could use several kinds of electrical appliances in the same time which would be similar to the people who acquire electricity from grid.
- People in the rural areas have the better in quality of life since those areas become the electrified area.
- Quality of farmer life in rural area will be improved due to the availability of electricity at affordable price. More people can have access to electricity and be able to use necessary conveniences such as electric lightings, fans and televisions.
- Turn Farmer Diesel Engine in nighttime to be hybrid power AC Machine.
- The system operates nearly similar to Thai farmer culture that one FDE can generate electricity by parent provider is able to support family child households in the cluster which is the mutual social and culture life of Thai farmer family community.

- Considerable saving in fuel cost will be achieved since the primary energy used to produce electricity is solar energy, which is free and unlimited.
- Considerable reduction in environmental pollution can be achieved because fossil fuel will be replaced by bio diesel fuel, resulting in less CO_2, SO_x and NO_x being released into the atmosphere.
- This project uses environmentally friendly method and renewable energy technology to produce electricity in a sustainable manner. Hence, CO_2 emission credit can be accrued due to its “clean” project status.
- This project can promote the spin-off of other renewable energy technology such as biogas technology, gasification of agricultural wastes, etc.
- Farmers can earn additional income when they sell their bio-products as supplementary fuels to the operator. This will result in a better distribution of wealth and sharing of benefits.
- For future prospects, this concept can be expandable to farmer households entire Mekong Region.

6.5 Project Dissimilation and Commercial Actions

Currently, solar home systems have been installed totally 203,000 households or about 500 villages. Since this systems have not been successful in some villages because of the stability and reliability problems. To solve these troubles by developing to PV diesel hybrid system could be the good prospect to enhance more reliability and stability of the system.

With the approval of appropriate technology, its well design that matched to social and culture behavior of the farmer and the mentioned benefits in previous section, it is believed that PV-Bio diesel from Farmer Diesel Engine for Hybrid Solar Home System [PV-Bio FDE for HSHS] project has a good opportunity to be consider as further system improvement program after SHS project. Due to a large amount number of farmer families which are 60%-70% of Thai population, it can create the big possibilities for many commercial activities and actions in the term of business.

Chapter 7 : Conclusion

The thesis has addressed the practical solution for non-electrified Thai farmers' households in rural area by looking the niches of former project, especially the huge project of 300,000 households, 120W Solar Home Systems (SHS).

Most local resources, adaptive equipments or even existing technologies, which are available in land, have been taken in first priority. By designing, the methodology can flexibly either follow optimum design rules or sometime adjust to follow existing resources limitation that farmers currently have. System allows possibility to use single FDE from parent source in the range of 8-12 HP. However, the constraints design criteria are PV Array will always follow in power range in multiple of 120 W according to number of family's community in cluster.

The Farmer Diesel Engine becomes the role player in this thesis to combine with obtained PV Array from other project to be PV-Bio Diesel from Farmer Diesel Engine for Hybrid Solar Home System [PV-Bio FDE for HSHS].

The results after implemented the system can be concluded in 4 perspectives:

1. Technical performance perspectives

   - The efficiency of PV-Modules (η_{PV}) is 6%-7%.
   - The efficiency of Bi-directional inverter (η_{inv}) is about 80% – 82 %.
   - The 6 months average of performance ratio (PR) is 70.60 %.
   - The 6 months average of solar fraction is 69.64 %.
   - The 6 months average of final yield is 3.54 hours/day.

2. Economic perspectives

   - Almost every farmer families normally own FDE, thus the cost of FDE has not been taken into account in Life Cycle Costs (LCC) analysis. Then the payback period of the system can be shorter.
   - PV-Modules are also not count in LCC analysis, because those modules were taken from other failed projects.
   - The total LCC (ALCC) result in analysis is 7,841.05 €
   - The total energy generated by the system is 20,984 kWh.
   - Electricity cost is 0.48 € / kWh (NPV).

3. Environmental perspectives

   - Daily FDE operation hours have been reduced from about 1-2 hours down to 30-50 minutes affected correspondingly to fuel costs reduction.
   - Noise pollution hours will be reduced according to operation hours.

Through out this work, the results of technical performance, economic and environmental assessment evaluation and analysis above confirm that PV-Bio FDE for HSHS is succeeded as stated follows:

- Technologies performance approved and well system functioning.
- System has more stability and reliability comparing to SHS.
- System Flexibility design and in line with Thai farmer social and culture.
- Farmers as the users able to use this innovative hybrid system with low investment because system allows to use most existing power generation equipments e.g. PV-Modules from SHS, FDE and AC Machine.
- This hybrid system can also supply the increasing farmer need of electricity when farmer would like to have more appliances for their comfort life.
- System is design for manual operation, less complexity and easy for self-maintenance by farmers.
- The use of FDE for generating electricity is regularly familiar for farmers.
- Costs of diesel fuel and noise pollution are reduced comparing to electricity generation by diesel AC Machine only.

The key success of the project is PV-Bio FDE for HSHS can operate nearly similar to Thai farmer culture that one FDE can generate electricity by parent provider is able to support family child households in the cluster which is the mutual social and culture life of Thai farmer family.

Outlook for future dissemination is to spread out this concept in nation wide to the area of farmer families who installed SHS and owned FDE. It can be also adaptable applied to Mekong region, which has almost similar culture to Thailand.

References

[1] Ministry of Energy (MOE), Thailand

[2] National Economic and Social Board (NESDB), Thailand

[3] Energy Planning and Policy Office (EPPO), Thailand, http://www.eppo.go.th

[4] PDP 2004, Power Development Plan of Thailand

[5] J. Schmid, "Photovoltaic systems Technology, teaching script", IEE-RE, University of Kassel, Germany, 2002.

[6] Shepherd, C. M, "Design of Primary and Secondary Cells II – An Equation Describing Battery Discharge", Journal of Electrochemical Society, Vol. 112, No. 7, July 1965. pg. 657-664

[7] Wenham, S.R, Green, M.A.; Watt, M.E., "Applied Photovoltaics", Australia. pg. 95-105.

[8] Sorokin, Alecsei, "Batteries and charge controllers for PV systems, in Fraunhofer Institute for Solar Energy Systems", Course book for the seminar, Photovoltaic Systems, Freiburg, 1995. pg. 109-142.

[9] PEA, Provincial Electricity Authority, Thailand

[10] Leonics company, Thaland

[11] Friedrich Sick, Thomas Erge, "Photovoltaics in Buildings", 1996 IEA

[12] W. Kleinkauf, Mohamed I. A. Ibrahim, "Decentralized Hybrid Renewable Energy Systems", a dissertation at University of Kassel, Germany, 2002.

[13] Markvart, T. (2000), "Solar Electricity," Second Edition, John Wiley & Sons, Ltd., pp. 123.

[14] Gabriele Seeling-Hochmuth, "Optimization of Hybrid Energy Systems Sizing and Operation Control", a dissertation at University of Kassel, Germany, 2001

[15] Britta Buchholz, "Smart Web Index and data exchange options", a dissertation at University of Kassel, Germany, 2001.

[16] Nguyen Minh Bao, “Study and Design of a Photovoltaic-Diesel Hybrid Ssystem for a Remote Village Electrification in Vietnam”, a Master thesis at Naresuan University, Thailand, 2000

[17] Hybrid Sizing and Economic Comparison Workbook, Siemens Solar Industries 1998-1999

[18] Boonyang Plangklag, “An Embedded Interactive Monitoring System for PV-Diesel Hybrid Plants in Rural Areas”, a dissertation at University of Kassel, Germany, 2005.

[19] David arap Cheruiyot Cherus, “Modelling, Similation, and Performance Analysis of a Hybrid Poer System for a Mobile Medicial Clinic”, a dissertation at University of Kassel, Germany, 2004

[20] http://www.108engine.com

[21] http://www.solar.com/pma2141.htm

[22] http://www.grantdataloggers.com

[23] http://www.cfs.co.uk

[24] http://www.indexmundi.com/

[25] http://cobweb.businesscollaborator.com

[26] http://www.un.org/Depts/Cartographic/map/

[27] Achitpon Sasitharanuwat, “Performance evaluation of a 10 kW_P PV power system prototype for isolated building in Thailand”, Physics Department, Faculty of Science, Uttaradit Rajabhat University

[28] Prof. Dr. Pumisak Intanon, Status of community energy from agricutural products, SERT, Naresuan University, Thailand