Optimization of Off-grid Hybrid Wind-Diesel Electrification in Thailand: A Case Study of Remote Island

Bundit Limmeechokchai and Prachuab Peerapong

Abstract— *This paper investigates the influence of energy efficiency in the process of sizing and optimization of operation of off-grid hybrid wind-diesel system for electric power supply to a remote island of 90 households in the south of Thailand. System sizing is optimized using HOMER model. The techno-economic analysis is used to investigate the hybrid wind-diesel power plant to serve the loads of the village. This study found that the use of efficient lamp and efficient electric appliances, which consume less electrical energy, reduces the time of operation of the diesel generator by about 15-20% in comparison with using only diesel generator. Furthermore, the results show that greenhouse gas emissions can be avoided by the proposed hybrid power plant.*

Keywords— **Off-grid electrification, Hybrid wind-diesel system, Optimization, Remote island, Techno-economic analysis.**

1. INTRODUCTION

During the past 15 years (1993-2009), electricity consumption in Thailand increased significantly from 63,279 GWh to 146,182 GWh and peak demand increased from 9,839 MW to 22,315 MW [1-2]. As of April 2009, peak demand of electric power system was recorded at 22,315 MW which was 78.4 MW or 0.35% higher than the record of 2008 and peak consumption of electricity was 146,182 GWh with 74.8 percent of load factor. As of December 2009, the total national capacity was 29,212 MW comprising 14,328 MW (49.0%) of EGAT's power plant, 14,243 MW (48.8%) of domestic private power producers (IPPs and SPP) and 640 MW (2.2%) of neighboring power purchase [1]. Energy Policy and Planning Office (EPPO) reported that total energy consumption in 2010 can be categorized by economic sectors: residential; 33,213 GWh (22.34%), commercial; 35,980 GWh (24.19%), industrial; 65,956 GWh (44.36%), agricultural sectors; 335 GWh (0.22%), and others 13,222 GWh (8.89%). The power forecasted in PDP 2010 for peak load demand in 2030 is approximately 52,890 MW or 2.37 times higher than that of 2009 (22,315 MW). The growth rate of the forecasted peak demand during 2010-2030 is 4.19 percent per year compared with 2.44 percent per year during 2005-2009. The forecasted energy demand in 2030 is about 347,947 GWh or 2.38 times higher than that of 2009 (146,182 GWh). An average growth rate of forecasted energy demand during 2010-2030 is 4.22% per year compared with 2.83% per year during 2005-2009. Thus, the long term load factor is between 74% and 75%. The Ministry of Energy has come up with a policy to develop the renewable energy (RE) and released the Alternative Energy Development Plan (AEDP) for a fifteen years period (2008-2022). The objective of AEDP is to increase the portfolio of renewable energy to 20.3% of the final energy consumption in 2022. At the end of the plan, the portion of renewable energy in power generation will be 2.4% or 5,608 MW. The electricity accessibility level in island areas in Thailand is very low due to long distance from the grid, and high cost of grid extension to the areas, compared with 98% accessibility rate in the urban area. In island areas, electricity is supplied by using diesel generators. Though diesel systems have their distinct advantages of electricity generation, but their operational and maintenance costs are high, especially at low loads, and storage & transportation of fuel to the remote island is also difficult. There is also a problem of oil leakage into the neighboring areas. In Thailand, application of renewable energy technologies (RETs) for rural and island areas, is increasing in recent years, but not very widespread. Therefore, the concept of wind-diesel hybrid electricity system is a reliable alternative energy source because it uses wind energy combined with diesel energy to create a stand-alone energy source to provide electricity in remote islands.

Bundit Limmeechokchai (corresponding author) is an Associate Professor at Sirindhorn International Institute of Technology. P.O. Box 22, Klong Luang, Pathumthani 12121, Thailand. Tel: +662-986-9009; Fax: +662-986-9112-3; E-mail: bundit@)siit.tu.ac.th.

Prachuab Peerapong is with Sirindhorn International Institute of Technology. P.O. Box 22, Klong Luang, Pathumthani 12121, Thailand. E-mail: prachuab@siit.tu.ac.th.

2. WIND-DIESEL OFF-GRID HYBRID MODEL

2.1 Wind energy as a source of renewable energy

In Thailand, the wind speed in island has high potential to produce electricity with an average speed of 5 m/s or more, depending on seasons and times of day. The probability density of the Weibull distribution (Patel, 2006) is commonly used for calculation of average available power in wind turbine per unit area. The Weibull distribution function (Weibull, 1957) is a two parameter function, which is written as:

$$f(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} \exp[-(\frac{v}{k})^{k}] \quad (1)$$

where k is the shape parameter, describing the dispersion of data, and c is the scale parameter, with the unit of speed (m/s). The two parameters c and k are related to the average wind speed by the following relation:

$$\bar{v} = c\Gamma(\frac{1}{k}+1) \quad (2)$$

where Γ is the gamma function. To fit a Weibull distribution to measured wind data, HOMER model uses the maximum likelihood method. The predicted and actual wind speeds are also investigated.

The wind energy (E) that can be extracted by a wind turbine is defined by the following equation:

$$E = T\int_0^\infty P(U)\cdot f(v)\cdot d(U) \quad (3)$$

where $f(v)$ is the probability density function of wind speed, $P(U)$ is the power curve of the turbine, and T is time period.

Using the equation (1) substitutes in equation (3), we can obtain the wind energy in terms as of Weibull distribution.

$$E = T\int_0^\infty (\frac{k}{A})(\frac{U}{A})^{k-1}\cdot \exp(-(\frac{U}{A})^k)P(U)\cdot d(U) \quad (4)$$

The capacity factor (C_f) is one element that enables to measure the productivity of a wind turbine. It compares the plant's actual production over a given period of time to the amount of power that the plant would have produced if it had run at full capacity of the same amount of time. It can be calculated by the following equation, and expressed in %.

$$C_f(\%) = \frac{\text{Wind energy produced (Wh/year)}}{\text{Max wind energy produced (Wh/year)}} \quad (5)$$

2.2 Diesel electricity generation in Thailand

The consumption of diesel to produce electricity in Thailand is only a small portion, and decreased significantly. For example, the annual consumption rate decreased from 177 GWh in 2005 to 45 GWh in 2009 or with the average of -12.6% annually. However, in remote areas or island or the areas that are off-grid connection, the diesel fuel-based for electricity production is the most alternative way to supply the most needed demand.

2.3 The hybrid configurations in Thailand

The most hybrid electricity configuration in Thailand for decentralized generation (DG) or off-grid electricity is diesel-PV hybrid system. The most successful case of diesel-PV hybrid system in remote island is installed in Kojig island located in Chantaburi province on the eastern coast of Thailand. This project was installed in 2004 through the cooperation of King Mongkut's University of Technology Thonburi, Kasetsart University and Mahidol University. Another alternative hybrid electricity configuration is diesel-wind turbine. With the limitation of wind potential in Thailand, the diesel-wind turbine is also a site specific. The most wind potential areas are in seashore coastlines or in islands. As the selected site for this study has a high wind potential. It is located 45 km from the main land in the gulf of Thailand.

3. METHODOLOGY

3.1 Optimization model

Hybrid systems consist of several renewable energy production structures and storage units. One has to consider lots of probability calculations while planning the proper hybrid system in order to respond to the energy demand. Hybrid Energy Performance Equations and the associated Energy Performance Curves are derived and introduced, respectively, which provide a visualization model, simplifying hybrid system analysis. The cost effectiveness of the present diesel system and the wind/diesel electricity for the remote island in the South of Thailand is evaluated employing the HOMER model, developed by the National Renewable Energy Laboratory (NREL), USA. HOMER is a powerful simulation tool, considering sustainability factors such as system efficiency, weather, fuel costs, O&M costs. Subsequently, simple novel HOMER software is a user friendly micro-power design tool that simulates and optimizes stand -alone and grid connected power systems. Recently, it has been used widely in the field of hybrid systems. It can be used with any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, micro-turbines, batteries, and hydrogen storage, serving both electric and thermal loads. HOMER expresses the economics of controllable energy sources with two values: fixed cost and energy cost per kWh. These costs represent the cost for generating energy at any time for a power source. HOMER searches for combination of sources meeting the load and then finds the system that achieves the goal with minimum costs. The advantage of the HOMER is that it can involve also all costs such as the initial capital and the maintenance costs including pollution penalties. The simulation considers one-year time period using minimum time-step of 1 minute. It performs a sensitivity analysis which can help the analyst to investigate the effects of uncertainty or changes in input variables. The Objective of the optimization simulation is to evaluate the economic and technical feasibility for a large number of technological options, while considering variations in technology costs and energy resources availability. Results obtained in this study show that combined power scheme is more sustainable in terms of electricity supply to the remote islands and in terms of avoided greenhouse gas emissions when compared to stand-alone diesel system.

3.2 Literatures review

Many literatures reported to determine the optimum hybrid energy system for small loads (ranging from few watts to few kilowatts) in a given location [3–6]. These studies showed that the renewable energy-based off-grid hybrid generation systems can compete with power from the gird in remote locations, where the grid is neither feasible nor nonexistent.

The hybrid systems such as wind/diesel are now proven technologies and options to supply small electrical loads at remote locations as reported by Lundsager and Bindner [7] and Zhang Hongyi et al. [8]. In developing countries, interest in medium to large-scale wind-diesel hybrid power system for rural electrification has grown enormously.

With growing global awareness of the need for clean sources of energy, wind energy in particular, many researches on scientific study are being carried out in Saudi Arabia. Rehman et al. [9] conducted a study to perform an economical feasibility assessment of an existing grid-connected diesel power plant supplying energy to a remote village by adding wind turbines in the existing power system in order to reduce the diesel consumption and environmental pollution, using the HOMER model. They found that the wind-diesel hybrid system becomes feasible at wind speeds above 6.0 m/s and a fuel price of 0.1$/L or higher.

3.3 Optimal wind turbine size selection

The optimal wind turbine size selection is based on results that are listed of best system configuration first, to worst system configuration last. The most important parameters to consider are the Cost of Energy (COE) and the Net Present Cost (NPC). So, the hybrid systems of wind turbines and diesel are based on wind potentials or wind velocities and diesel prices. The system includes battery banks for energy storages and inverters for converting DC to AC electricity. The least cost of COE and NPC of the system is the optimal solution. For example, when the wind velocities and diesel prices are both high, the selected wind turbine optimal size is also high in terms of renewable energy (wind) penetrations. In contrast, when the wind potential and diesel prices are both low, costs of wind turbine system are high. In this case, it means that it could not be competitive with only diesel systems, the wind turbine optimal size selected is also low in terms of renewable energy (wind) penetrations, or the only diesel system is the optimal case. Therefore, the variation of input values is needed for both annual average wind speeds and diesel prices to perform sensitivity analysis on these variables. HOMER software allows the users to explore variations in average annual wind speed and diesel prices affecting the optimal design of the system.

3.4 Wind data collection and power demand

The wind data and electrical power demand was collected by Provincial Electricity Authority (PEA). The system is consisted of the tiled-up tower with 40 meters in height, instrument, sensors, and accessories. During January-December 2009, wind data and electricity demands were collected. Performances of wind power are obtained, processed and analyzed using HOMER optimization model.

4 PLANT DESCRIPTIONS

Ko Tao is used as a model for study of wind-diesel off-grid hybrid electrification for remote island. It is a small famous tropical island, destination for tourism. It is located on southeast coast of Thailand (latitude 10.06 N°, longitude 99.83°E), about 45 km from Chumphon Province. The 33 kV electric system is supplied by 6 small diesel generators with a capacity of approximately 3,000 kW operated by PEA. The system peak load demand consumed by 920 habitants, is nearly 3,000 kW as of April 2009. It can be seen that the system is needed to extend more power generators in the future to meet the increased demand. The wind-diesel is a good option to consider with much potential of wind and in terms of environmental concerns. The map of island is shown in Fig.1. The island is fully mountain area and tropical forest. There is no electrification in the areas since it is difficult to extend the diesel-based PEA small grid and being of diesel generation limit.

Fig. 1 Map of Ko Tao, 45 km from the coast of Thailand.

5 WIND-DIESEL HYBRID OPTIMIZATION

5.1 The electricity load demand by the islander

The monthly mean wind speed of this island is shown in Fig.2. The annual peak load is approximately 3,000 kW observed in April. The higher demand exists from March to July due to high season for tourism while relatively lower in September to November due to low season for tourism.

The energy consumption mostly depends on diesel generation. The increased demand is due to its famous destination for tourism and its population growth.

5.2 Wind speed data

The wind data were collected at the height of 40 meters above the ground level. The 250 kW wind turbine rotor are placed at the hub height at 50 meters by using 1/7 power law. At 50 meter height the average wind speed became 5.48 m/s as shown in Fig. 3.

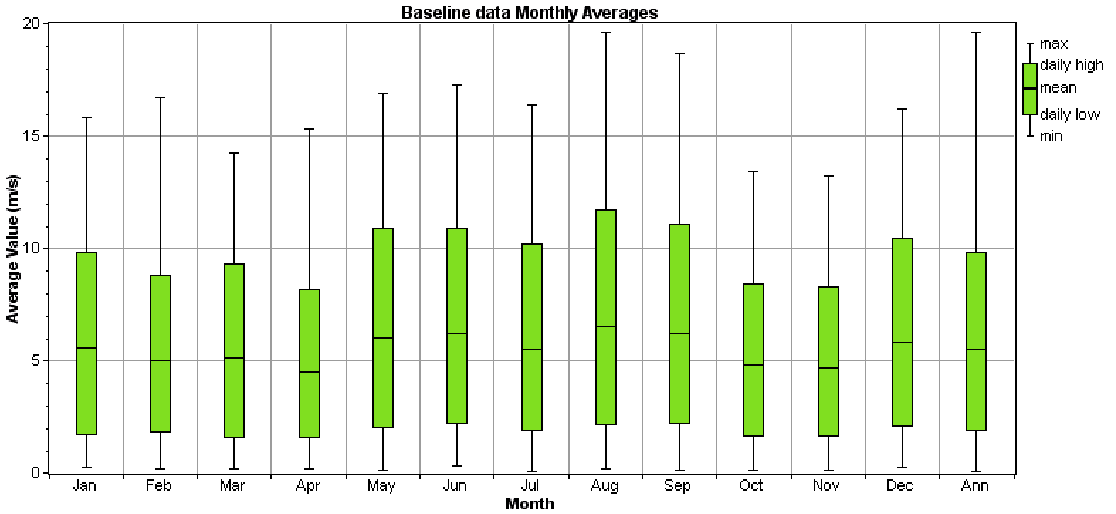


Fig.2 Variation of mean wind speed during January-December 2009.

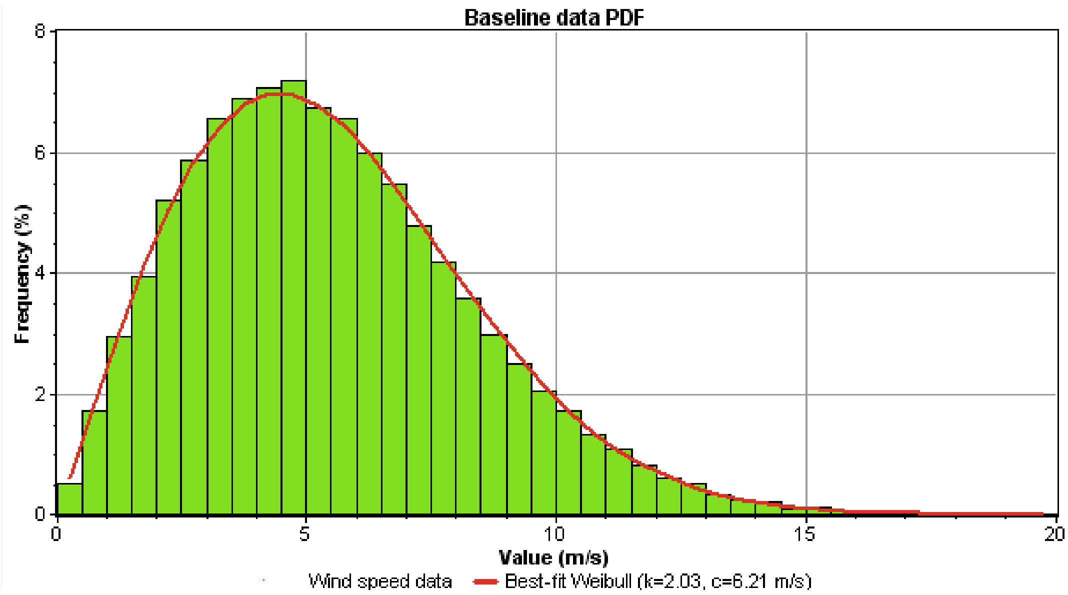


Fig.3 Hourly mean wind speed distribution.

Table 1. Diesel generator information

Parameters	Value/ information
Rated power	500 kW
Minimum allowable power	74 kW
Full load fuel consumption	140 L/hr
Power factor	0.82
Voltage	400 V
Rated current	902 A
Frequency	50 Hz
Rotating speed	1500 rpm
Battery (voltage)	24 V

Table 2. Diesel generator data

Rating kW	Capital cost (US$)	Replacement (US$)	O&M cost (US$/hr)
500	80,355	53,570	0.301

Table 3. Fuel cost and technical data

Parameter	Value
Cost	0.75 US$/L
Lower heating value	45.62 MJ/kg
Density	0.831 kg/L
Carbon content	80%

5.3 System components

The main components of an isolated grid-connected wind-diesel hybrid system are 3 diesel generators and a 250 kW wind turbine. The diesel system consists of generator 1 with capacity of 1,500 kW, generator 2 with capacity of 1,000 kW, and generator 3 with capacity of 500 kW. The cost of each component, the economical and control parameters required by the HOMER software are discussed in the forthcoming paragraphs. The overall system includes converter and battery as shown in Fig. 4

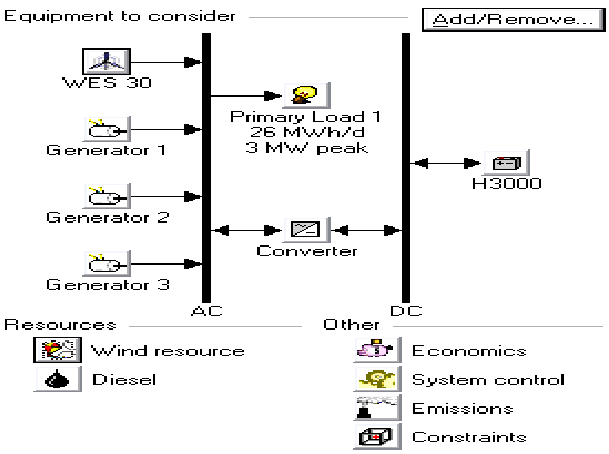


Fig. 4 Wind-diesel energy system for an isolated grid.

Table 4. Wind turbine technical data

Parameter	Value/ information
Rated power	250 kW
Cut in speed	3.5 m/s
Cut out speed	22.0 m/s
Rotor diameter	28.5 m
Hub height	50 m
Voltage	400 V
Rated current	410 A
Frequency	50 Hz
Rotating speed (High/Low)	39.8/26.5 rpm
Wind turbine capital cost ($)	250,000
Replacement cost ($)	175,000

Table 5. Converter and battery cost

Cost	Capital ($)	Replacement ($)	O&M ($/yr)
Converter			
Cost per kW	150	100	0.1
Battery			
Cost per set	420	360	0.2

5.3.1 Diesel generator

The diesel power plant consists of 6 units of 500 kW rated capacity; three units for generator 1, two units for generator 2, and one unit for generator 3. The details of each unit in terms of both technical data and the cost data are shown in Tables 1 and 2, respectively. Table 3 shows the fuel cost and its technical data.

The operation and maintenance cost of 0.301$/hr was used in the simulation. The fuel costs are obtained locally, including the transportation cost of 0.80 $/L, as given in Table 3. This table also includes technical information related to diesel fuel.

5.3.2 Wind turbine

The other major component of the wind-diesel hybrid system after the diesel-generating set is the wind energy conversion system.

The modern wind machines are very efficient and are found in big sizes. Today's standard market size of the wind turbine is greater than 1.5 MW. The rotor diameter of these machines varies between 40 and 110 m or more.

The modern wind turbine produces more energy due to high wind speeds at higher hub heights, since the energy yield from the wind energy conversion system depends on the availability of wind and its variation. In this case, WES30 of 250 kW from Wind Energy Solutions manufacturer is used. The technical and cost information of the wind machines is summarized in Table 4. The annualized operation and maintenance cost of $1,500 per wind turbine has been used for analysis.

5.3.3 Converter and battery

A battery bank consists of 24V H3000 batteries and inverters. The battery nominal capacity was 3000 Ah per set. It is noted that the converter functions as both an inverter (converting DC to AC) and converter (AC to DC). The costs of converter and battery are shown in

6 RESULTS AND DISCUSSION

HOMER provides results in terms of optimal systems and sensitivity analysis. In the analysis, the optimized results are presented on a particular set of sensitivity parameters. The results are presented in the following paragraphs.

6.1 Optimization results

The optimization results for a wind speed of 5.5 m/s and a fuel price of 0.80 $/L are summarized in Fig.7. In this case, a diesel power system seems to be most economically feasible with the minimum total net present cost (NPC) of $35,619,588 and minimum energy cost (COE) of 0.288$/kWh, although the system represents a higher initial capital when compared to the system run by diesel only. Generally, at wind speed less than 4 m/s, the only diesel system was found to be most feasible solution with COE, less than 0.277 $/kWh corresponding with a diesel price of 0.7 $/L.

As seen from Fig.8, about 55% of initial cost of wind-diesel hybrid system was accounted for diesel power system, and 98.6% of the operation and maintenance cost and fuel cost were accounted for diesel system. The total annualized cost for wind equipment including converter and battery system are accounted for $80,187 (3% of the entire wind-diesel power plant cost), while for diesel power system is accounted for $ 2,706,218 (97% of the entire wind-diesel power plant cost). The energy yield from different components of the wind-diesel power plant cost is shown in Fig. 6 for the total energy requirement of the island. The wind machine produced 313,428 kWh/yr (3% of the total energy served), while the diesel generators produced 9,482,455 kWh/yr. The system with battery back-up was almost no excess electricity with any capacity shortage, as shown in Fig. 7.

Sensitivity Results | Optimization Results

Sensitivity variables

Wind Speed (m/s) 5.5 Diesel Price ($/L) 0.8

Double click on a system below for simulation results. Categorized ◉ Overall

WES30	Label (kW)	Label (kW)	Label (kW)	H3000	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)	Label (hrs)	Label (hrs)
1	1500	1000	500	250	300	$ 880,000	2,717,564	$ 35,619,588	0.288	0.03	3,184,694	3,425	3,924	2,229
1	1500	1000	500	200	300	$ 859,000	2,719,301	$ 35,620,796	0.288	0.03	3,186,823	3,455	3,939	2,187
1	1500	1000	500	300	300	$ 901,000	2,716,852	$ 35,631,488	0.288	0.03	3,183,429	3,412	3,897	2,266
1	1500	1000	500	350	300	$ 922,000	2,715,902	$ 35,640,340	0.288	0.03	3,182,141	3,393	3,900	2,274
1	1500	1000	500	400	300	$ 943,000	2,715,350	$ 35,654,288	0.289	0.03	3,181,336	3,382	3,892	2,294
1	1500	1000	500	200	250	$ 851,500	2,722,823	$ 35,658,316	0.289	0.03	3,197,992	3,699	3,936	2,062
1	1500	1000	500	250	250	$ 872,500	2,722,418	$ 35,674,132	0.289	0.03	3,197,164	3,685	3,935	2,077
1	1500	1000	500	300	250	$ 893,500	2,722,450	$ 35,695,540	0.289	0.03	3,196,758	3,681	3,927	2,089
1	1500	1000	500	350	250	$ 914,500	2,722,396	$ 35,715,852	0.289	0.03	3,196,363	3,673	3,931	2,092
1	1500	1000	500	400	250	$ 935,500	2,723,283	$ 35,748,200	0.289	0.03	3,196,176	3,672	3,928	2,095
1	1500	1000	500	300	500	$ 931,000	2,738,578	$ 35,939,220	0.291	0.03	3,180,158	3,008	4,144	2,216
1	1500	1000	500	350	500	$ 952,000	2,737,430	$ 35,945,540	0.291	0.03	3,178,550	2,992	4,116	2,241
1	1500	1000	500	250	500	$ 910,000	2,741,664	$ 35,957,668	0.291	0.03	3,183,946	3,089	4,112	2,188
1	1500	1000	500	400	500	$ 973,000	2,736,760	$ 35,957,972	0.291	0.03	3,177,302	2,947	4,152	2,240
1	1500	1000	500	200	500	$ 889,000	2,744,885	$ 35,977,848	0.291	0.03	3,187,994	3,168	4,090	2,180
1	1500	1000	500	300	600	$ 946,000	2,748,981	$ 36,087,208	0.292	0.03	3,180,279	3,010	4,141	2,216
1	1500	1000	500	350	600	$ 967,000	2,747,673	$ 36,091,476	0.292	0.03	3,178,510	2,990	4,118	2,240
1	1500	1000	500	400	600	$ 988,000	2,747,057	$ 36,104,608	0.292	0.03	3,177,325	2,946	4,153	2,240
1	1500	1000	500	250	600	$ 925,000	2,752,168	$ 36,106,944	0.292	0.03	3,184,161	3,090	4,111	2,188
1	1500	1000	500	200	600	$ 904,000	2,755,189	$ 36,124,556	0.292	0.03	3,188,027	3,168	4,091	2,178
	1500	1000	500	300	300	$ 651,000	2,792,682	$ 36,350,844	0.294	0.00	3,281,072	3,546	3,919	2,180
	1500	1000	500	250	300	$ 630,000	2,794,551	$ 36,353,736	0.294	0.00	3,283,357	3,586	3,911	2,157
	1500	1000	500	200	250	$ 601,500	2,796,827	$ 36,354,328	0.294	0.00	3,293,704	3,845	3,896	2,039
	1500	1000	500	200	300	$ 609,000	2,796,589	$ 36,358,792	0.294	0.00	3,285,959	3,623	3,928	2,111
	1500	1000	500	250	250	$ 622,500	2,795,841	$ 36,362,736	0.294	0.00	3,292,412	3,825	3,898	2,053

Fig. 5. Optimization for wind speed of 5.5 m/s, diesel price of 0.8$/L and renewable energy fraction of 3%

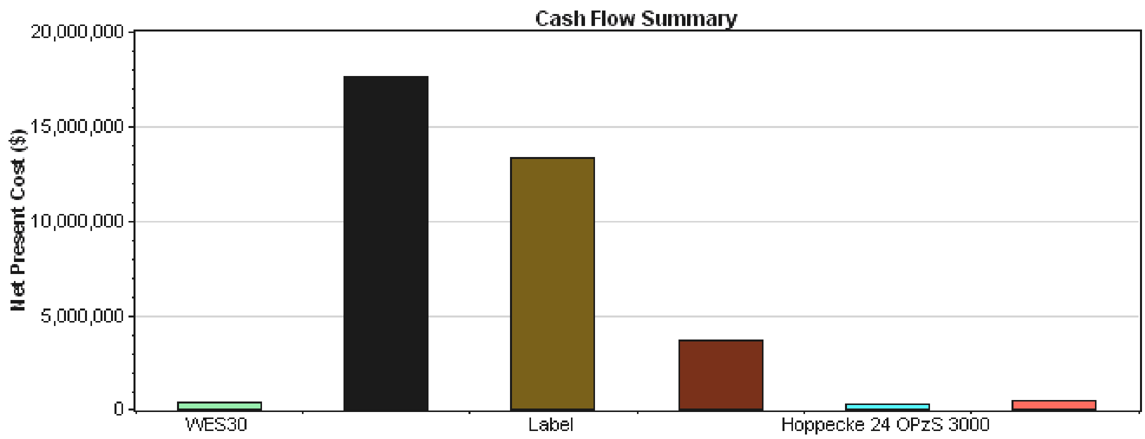
System Architecture: 1 WES 30 | 500 kW Generator 3 | 300 kW Rectifier
1,500 kW Generator 1 | 250 Hoppecke 24 OPzS 3Cycle Charging
1,000 kW Generator 2 | 300 kW Inverter

Total NPC: $ 35,619,588
Levelized COE: $ 0.288/kWh
Operating Cost: $ 2,717,564/yr

Cost Summary | Cash Flow | Electrical | WES30 | Label | Label | Label | Battery | Converter | Emissions | Hourly Data

Cost type: ◉ Net present ○ Annualized ☑ Reverse sign

Categorize: ◉ By component ○ By cost type ☐ Show details



Compare...

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
WES 30	250,000	73,021	19,175	0	-13,592	328,605
Generator 1	240,000	397,972	394,047	16,580,762	-10,907	17,601,876
Generator 2	160,000	316,168	300,971	12,600,330	-11,468	13,366,002
Generator 3	80,000	77,066	85,482	3,387,791	-3,553	3,626,788
Hoppecke 24 OPzS 300	105,000	89,104	63,917	0	-371	257,650
Converter	45,000	12,518	383,501	0	-2,330	438,689
System	880,000	965,850	1,247,094	32,568,886	-42,221	35,619,608

Fig. 6. Cost analysis of wind-diesel hybrid power system of island electrification.

System Architecture: 1 WES 30 | 1,500 kW Generator 1 | 1,000 kW Generator 2 | 500 kW Generator 3 | 250 Hoppecke 24 OPzS 3Cycle Charging | 300 kW Inverter | 300 kW Rectifier

Total NPC: $ 35,619,588
Levelized COE: $ 0.288/kWh
Operating Cost: $ 2,717,564/yr

Cost Summary | Cash Flow | Electrical | WES30 | Label | Label | Label | Battery | Converter | Emissions | Hourly Data

Production	kWh/yr	%
Wind turbine	313,428	3
Generator 1	4,841,291	49
Generator 2	3,672,731	37
Generator 3	968,439	10
Total	9,795,889	100

Consumption	kWh/yr	%
AC primary load	9,664,478	100
Total	9,664,478	100

Quantity	kWh/yr	%
Excess electricity	0.0830	0.00
Unmet electric load	0.0215	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.0320

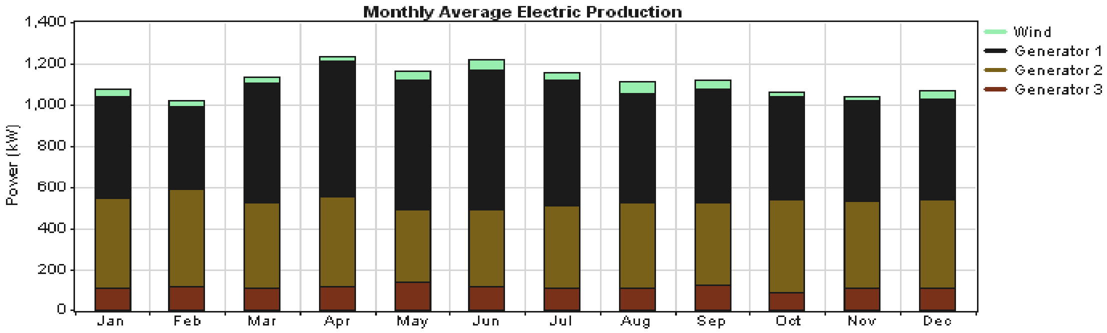


Fig. 7. Monthly energy yield from wind-diesel hybrid electrification for the island electrification

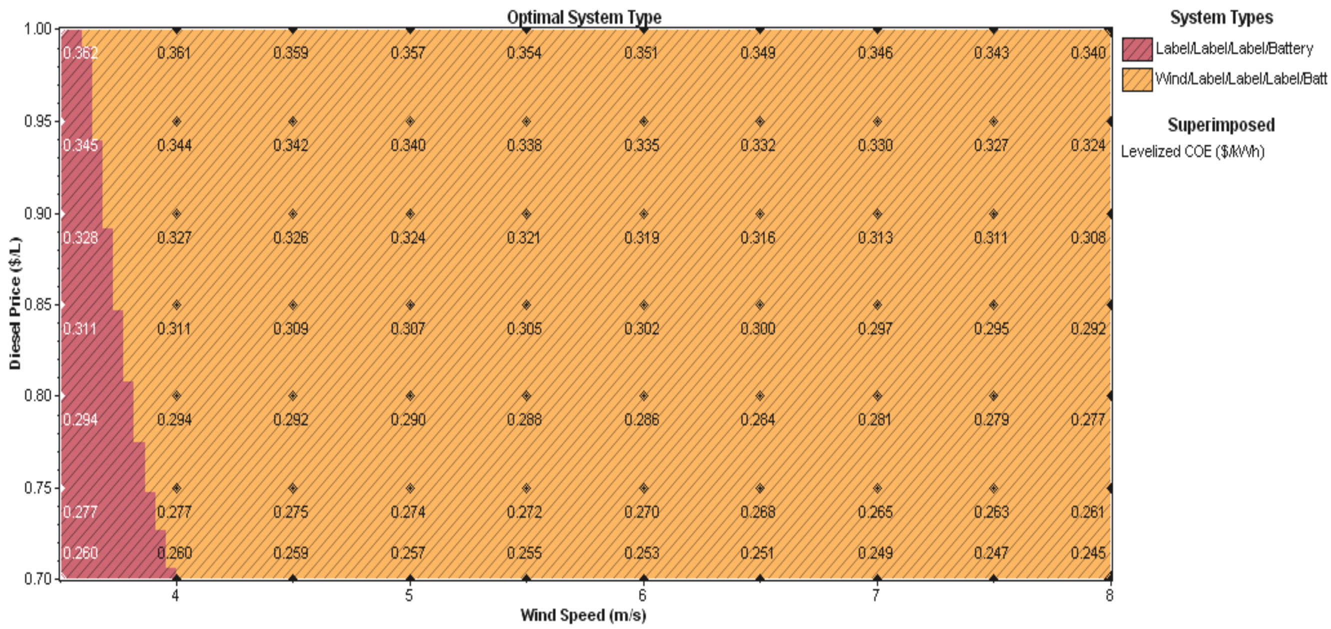


Fig. 8. Optimized wind-diesel hybrid system for island electrification.

Pollutant	Emissions (kg/yr)
Carbon dioxide	8,640,141
Carbon monoxide	21,327
Unburned hydrocarbons	2,362
Particulate matter	1,608
Sulfur dioxide	17,351
Nitrogen oxides	190,302

Fig. 9. GHG from diesel system

Pollutant	Emissions (kg/yr)
Carbon dioxide	8,386,349
Carbon monoxide	20,701
Unburned hydrocarbons	2,293
Particulate matter	1,561
Sulfur dioxide	16,841
Nitrogen oxides	184,712

Fig. 10. GHG from wind-diesel hybrid system

6.2 Sensitivity results

The HOMER eliminates all feasible systems and presents the results in ascending order of NPC. In this present case, wind speeds (3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0 m/s), and diesel prices (0.7, 0.75, 0.80, 0.85, 0.90, 0.95 and 1.0 $/L) were used as sensitivity variables. However, when the different interest rates are included, the cost of energy or electricity price slightly changes. For example, interest rate in this calculation is 7.5%, the cost of energy (COE) or electricity price is 0.288 $/kWh. The sensitivity studies showed that when interest rates are increased to 8.5% and 9.5% COEs are constantly increased to 0.293 $/kWh or increased by 1.73%. In contrast, when interest rates are decreased to 6.5% and 5.5%. COEs are decreased to 0.273 $/kWh and 0.258 $/kWh or decreased by 5.5 % and 5.8%, respectively.

The optimization results are shown in terms of wind speed and diesel prices, as shown in Fig.5. This type of graphical representation of optimal system-type provides information that a particular system will be optimal at certain wind speed and a certain fuel cost. Furthermore, the wind speed and diesel cost are usually site-dependent, so one can conclude that at a particular wind speed and fuel cost the system will be optimal for a particular place or location.

The hybrid wind-diesel optimal system for this network shows that the cost of energy or electricity price is 0.288 $/kWh or 8.68 Baht/kWh in comparison with a retail price of 0.116 $/kWh or 3.50 Baht/kWh from the national grid. When the network operation is optimized, it shows that the cost of energy or electricity price in wind-diesel system can be decreased significantly compared to the energy production cost on diesel generator-based or decreased from 0.348 $/kWh to 0.288 $/kWh or decreased with 0.06 $/kWh. It can be saved 587,753 $/year.

6.3 Greenhouse gases (GHG) reduction

The GHG pollutes the environment, which adversely affects the life of human beings. An indirect or hidden cost, which is not taken into consideration while using fossil fuels, is paid by the human beings. The diesel power system being used at this island emits 8,873,091 kg of pollutants into the local atmosphere of the island every year. The wind-diesel hybrid system can reduce pollutants to 8,612,457 kg per year. It shows a reduction of 260,634 kg of pollutants per year. The concentrations of various constituents of pollutants like CO_2, CO, nitrogen, etc. for diesel and hybrid system are summarized in Fig.9 and Fig.10, respectively.

7 CONCLUSIONS

The aim of this study is to perform an economical feasibility of an existing grid-connected diesel power plant supplying energy to a remotely located village by adding wind turbine in the existing power system in order to reduce the diesel consumption and environmental pollution, using the HOMER simulation model. It was found that in this study the wind-diesel hybrid system becomes optimized at wind speed above 5.5 m/s and fuel price of 0.80 $/L or higher. In the case, wind turbine was accounted for only 3% of energy consumption. The feasibility expansion of wind-diesel hybrid to other remote island is studied for the near future.

ACKNOWLEDGMENT

Authors acknowledge the Provincial Electricity Authority for the support of wind data and electricity load demand in this island, Sirindhorn International Institute of Technology, Thammasat University for the research fund, and National Renewable Energy Laboratory (NREL) for the support on HOMER model for this study.

REFERENCES

[1] Electricity Generating Authority of Thailand. Thailand Power Delvelopment Plan 2010-2030 (PDP 2010). Electricity Generating Authority of Thailand; 2010. pp.17.

[2] Energy Policy and Planning Office. Energy Statistics. 2010. Energy policy and Planning Office. Ministry of Energy, Bangkok.

[3] Lipman NH. (1994) Overview of wind/diesel systems. *Renewable Energ*, 5 (Part I), pp. 595–617.

[4] Bagul AD, Salameh ZM, Borowy B. (1996) Sizing of a stand-alone hybrid wind-photovoltaic system using a three-event probability density approxi-mation. *Solar Energy* , 56(4), pp. 323-35.

[5] Beyer H.G., Langer C. (1996) A method for the identificationof configurations of PV/wind hybrid systems for thereliable supply of small loads. *Solar Energy*, 57, pp. 381-91.

[6] Markvart T. 1996. Sizing of hybrid photovoltaic-wind energy systems. *Solar Energy*, 57(4), pp.277–81.

[7] Lundsager P, Bindner H. (1994). A simple, robust and reliable wind dieselconcept for remote power supply. *Renew Energy*, 5 (Part I) pp.626–30.

[8] Zhang Hongyi N. et al. (1996). The development and review of wind/diesel systems of the world. *New Energy* (Chongqing, China) , 18(6), pp.1–8.

[9] Rehman S., El-Amin I.M., Ahmad F., Shaahid S.M., Al-Shehri A.M., Bakhashwain J.M., Shash A. (2007). Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant. *Renewable and Sustainable Energy Rev*, 11, pp.635–53.