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Analysis and Sizing of Mini-Grid Hybrid Renewable Energy System for Islands

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ABSTRACT This paper aims to investigate the techno-economic feasibility analysis of stand-alone diesel system, stand-alone PV/storage system, PV/diesel hybrid system, PV/diesel/storage hybrid system for the Pratas island in Taiwan. The power supply of outlying islands in Taiwan still use fossil fuel generators. The fuel cost is higher than that of on shore of Taiwan, and it has a great impact on the environment. This problem can be mitigated by hybrid energy systems. Through the investigation to know the existing generator set and Photovoltaic (PV) operating status, load consumption, etc., the study collects the required data for statistical meteorological analysis and economic analysis, and uses Hybrid Optimization Models for Energy Resources (HOMER) to simulate techno-economics of the stated hybrid energy systems. The analysis contains the capital cost, net present cost (NPC), cost of energy (COE) and fuel saving in different capacities for each power supply system with different constraints. From the simulation results, the lowest COE is 0.3569 $/kWh that can be found at the PV/diesel hybrid system configuration scheme with a total PV system capacity of 200 kWp, the renewable fraction (RF) is 15.3% and the excess electricity fraction is 2.6%, which is lower than the generally acceptable 5%. Although the COE of PV/diesel/storage hybrid is higher than that of stand-alone diesel system, the annual total CO2 emissions is reduced by 31.63%, which is of great benefit to environmental protection.

INDEX TERMS Cost of energy, distributed generation, energy storage, hybrid power system, mini-grid, renewable energy.

I. INTRODUCTION

Energy is considered as a crucial contributor to the development of societies. Fossil fuel is the main source of electricity and discharges large amounts of toxic gasses into our atmosphere. Renewable sources such as solar photovoltaics, wind, biomass, small hydropower, etc. are nowadays commonly used to alleviate fossil fuel demand and mitigate environmental pollution [1]–[3]. A stand-alone generation of electricity from renewables become an attractive option for remote communities that cannot be viable to the main power grid [4], [5]. Moreover, the consideration of renewable energy sources has become necessary due to the ever rising oil prices as well as the environmental challenges associated with greenhouse gas emission [6]–[10]. However, power quality, stability and reliability, are main problems for renewable energy sources because of their unpredictable, seasonal, and time-dependent natures. Instead, hybrid power generation in remote areas is a more cost-effective option as compared to grid connected [11]–[16]. Adding energy storage system (ESS) for bi-directional power flow allows the storage of excess energy during the day and sustains the intermittent and night-time load demand [17]–[19]. The role of ESSs has increased in a variety of power system applications, such as enrichment of grid stability, improvement of energy system performance, voltage-frequency regulation services and reduction of environmental impact of fossil fuel consumption [20], [21].

Several research on standalone PV, grid-connected PV and hybrid systems for rural electrification have been carried out worldwide. Khatib *et al.* [22] optimized the building integrated PV / diesel hybrid system in Malaysia and proposed that PV-diesel is more feasible than a stand-alone PV or diesel system because it minimizes system costs by 35%. Rehman and Al-Hadhrami [23] presented an analysis of a village in Saudi Arabia on PV / diesel hybrid power system with battery backup. In [24], a research carried out in Palestine

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TABLE 1. Hybrid energy systems with various storage technologies.

Hybrid energy systems	Storage	Operating strategy	Grid connection	Methodology	Performance measures
PV/Diesel/Battery [25]	LA	LF	Off-grid	HOMER	NPC, COE, RF ,CO2 emissions
PV/Diesel/Batt [3]	LA, Li-ion	LF,CC,CD	Off-grid	HOMER	NPC, COE, EE, RF, DF, CO2 emissions
PV/Diesel/Batt [13]	LA	LF	Off-grid/grid connected	HOMER	NPC, COE,RF, CO2 emissions
PV/Diesel/Batt [14]	LA	-	Off-grid	HOGA	NPC, CO2 emissions
PV/Diesel/Batt [23]	LA	LF	Off-grid	HOMER	NPC, COE, EE, CO_2 emissions
PV/Diesel/Batt [29]	LA	LF	Off-grid	HOMER	NPC, COE, EE, O&M cost, CO2 emissions
PV/Diesel/Batt [2]	Li-ion	CC	Off-grid	MATLAB	NPC
PV/Wind/Diesel/Batt [12]	CELLCUBE	LF	Off-grid/grid connected	HOMER	NPC, COE,RF, CO2 emissions
PV/Wind/Biogas/Diesel/Batt [4]	LA	-	Off-grid	HOMER	NPC, COE, RF, O&M cost
PV/Wind/Biogas/Batt [11]	LA	LF, CC	Off-grid	HOMER	NPC, COE,RF, CO2 emissions
Wind/Diesel/Batt [28]	LA, Li-ion	LF, CC	Off-grid	HOMER	NPC, COE,RF, CO2 emissions
PV/Wind/Diesel/Batt [27]	Not specified	-	Off-grid	MBA	NPC,COE, Energy not supplied

Key: **CC**: Cyclic Charging; **CD**: Combined Dispatch; **DF**: Duty Factor; **EE**: Excess Energy; **COE**: Cost of Energy; **HOGA**: Hybrid Optimization by Genetic Algorithms; **LA**: Lead Acid; **Li-ion**: Lithium –ion; **RF**: Renewable Fraction; **MBA**: Modified Bat Algorithm

showed that the uses of PV / diesel hybrid systems in isolated locations are more cost-effective than stand-alone diesel generators or grid extensions. Halabi *et al.* [25] taken into account two distributed power stations in Sabah, Malaysia; each has various combinations of photovoltaic (PV), diesel generators, converters and storage batteries. Lau *et al.* [26] studied the possible use of PV/ Diesel engine driven hybrid energy system under Malaysian condition using HOMER and indicated that the system could be used to replace existing or upgrade diesel generation systems in remote areas. Shivaie *et al.* [27] considered a reliability constrained model for the optimal sizing of autonomous hybrid energy system using modified bat algorithm. Zhou *et al.* [28] conducted a study on techno-economic performance of stand-alone hybrid energy systems in the cold region of China. Some research works have assessed the techno-economic feasibility and usage capacity of various hybrid system configurations in remote locations [12], [29]–[32]. On the other hand, sizing and optimization of a hybrid renewable based farm in a stand-alone context and the market analysis related to demand side management have been the issues considered in different scholars [33], [34]. Table 1 describes some of the hybrid energy systems with various storage technologies and efficiency assessment requirements found in the literature [3].

This research focus on the techno-economic simulation of mini-grid hybrid power system on Pratas island for several reasons; Firstly, a number of islands worldwide rely on costly imports of fossil fuels for the generation of electricity. Secondly, solar and/or wind resources are highly available on most small islands as a regional source of energy [35]. Thirdly, small islands may illustrate technological and political viability of introducing high renewable energy contributions in order to serve as positive models for larger regions and countries. In addition, mixing of energy sources improve the efficiency of generation as the deficiencies of any component are reimbursed by the choice of other but appropriate components and their size is vital in the design of the system [36]–[40].

About 98% of Taiwan's energy depends on imports, Taiwan is actively developing renewable energy applications to increase energy autonomy and reduce fossil fuel use. The policy plans to increase renewable energy to 20% in 2025, increase natural gas to 50%, and reduce coal to 30%. Among them, the amount of PV power will reach 20GW, and amount of wind power generation will reach 6.7GW. Because of many of the islands in Taiwan still rely on diesel power supply, complying with the government's energy policy, by increasing the proportion of renewable energy, it will reduce fuel and reduce environmental pollution, and the appropriate proportion of renewable energy and COE must be considered at the same time. In the literature review, it is found that the research on the optimal capacity and cost of PV/diesel/storage hybrid system in Taiwan is lacking. In order to provide the capacity and cost of the mini-grid system in line with the actual use conditions, the researchers must collect weather data, statistics on the local load profile changes, local interest rate and inflation rate, fuel price, equipment costs, etc. and then conduct the techno-economic simulation and sensitivity analysis of each mini-grid system combination type to propose the capacity with the lowest COE.

In the optimal hybrid energy system (HES) capacity analysis method, it has been found from the literature review that the economic analysis of the same RF conditions lacks the constraints of considering the excess electricity fraction, and the discussion of the correspondence between RF and excess power is less mentioned. For more precise analysis

(a)

(b)

FIGURE 1. **Pratas island a) satellite photo and b) existing 40kWp PV system.**

and effective use of energy, the simulation analysis of HES in this study is to limit the excess electricity fraction to within the generally acceptable 5%, and to find the lowest COE of HES under different RF conditions. However, impacts of renewable energy on the reliability and quality of power system will be a future study.

II. METHODOLOGY

The research in this article is mainly to perform a techno-economic analysis of the mini-grid hybrid renewable energy system, which includes the analysis of the COE of stand-alone PV/storage system under different capacity shortage fraction conditions, the PV/diesel system capacity with the lowest COE can be found by changing the PV capacities, and the PV/diesel/storage hybrid system considers the limits of excess electricity fraction under different RF percentage intervals and finds the capacity of lowest COE of each RF percentage intervals. The techno-economic analysis results of stand-alone PV/storage system, PV/diesel hybrid system and PV/diesel/storage hybrid system are compared with stand-alone diesel system. Summation of the research method and discussion are as follows:

- The operation status of the generator and the 40kWp PV system, load power consumption on the island are properly considered. In addition, statistics on the diesel prices, interest rates, and inflation rates in Taiwan in recent years through the Chinese Petroleum Corporation, Central Bank of the Republic of China Taiwan) and survey the cost of equipment from the Taiwan market respectively to obtain the simulation data.
- According to the load conditions on the island, the suitable new generator set capacity is analyzed through the HOMER software. In addition, selection of the corresponding commercial diesel generator specifications to analyze the electrical characteristic and economic stand-alone diesel system are taken in to consideration.
- According to the load conditions, climatic conditions on the island, the electrical characteristic and economic feasibility under capacity shortage fraction of 0%, 5%, and 10% for PV/storage system are simulated, and discuss the variation of its simulation results.
- The electrical characteristic and economic feasibility under different PV capacities for PV/diesel system are simulated, and the PV capacity of the lowest COE is determined.
- Set the RF range between 10-45% to simulate PV/diesel/storage system and the interval is 5%. Find PV and storage capacity configurations that meet the excess electricity fraction below 5% and the lowest COE in each step and the lowest COE system capacity configuration may be obtained.

For the high RF conditions, the appropriate PV/diesel/storage system capacity configuration is used to analyze sensitivity of parameters such as global horizontal irradiation data (GHI), load consumption, price of diesel fuel, real interest rate, and capital cost so as to the discuss the impact on the economy, electricity, CO2 emissions of the system.

A. LOCATION AND BACKGROUND OF THE AREA STUDY

Pratas island is about 240 nautical miles from Kaohsiung, Taiwan (longitude: 116.731°, latitude: 20.699°). It is mainly composed of atolls, as shown in fig. 1 [41]. The island has become the Dongsha Atoll National Park on January 17, 2007. Currently, the island has a Marine National Park Management Office, a Marine Research Station, and the Taiwan Ocean Commission Sea Patrol Department to conduct marine ecological conservation, research, and maritime emergency assistance. The average number of people on the island is about 220 daily.

The electricity on the island is generated by four diesel generators (each capacity is 500kW) in turn for 24 hours. In 2016, a 40kWp PV system was added in parallel with the diesel generator to discuss the benefits of hybrid power supply. The diesel generator set has been in operation for 13 years. Because the high salt environmental conditions on the island and the quality of diesel generators, the maintenance frequency of each generator set has been increasing in recent years, and the solar photovoltaic system is unable to

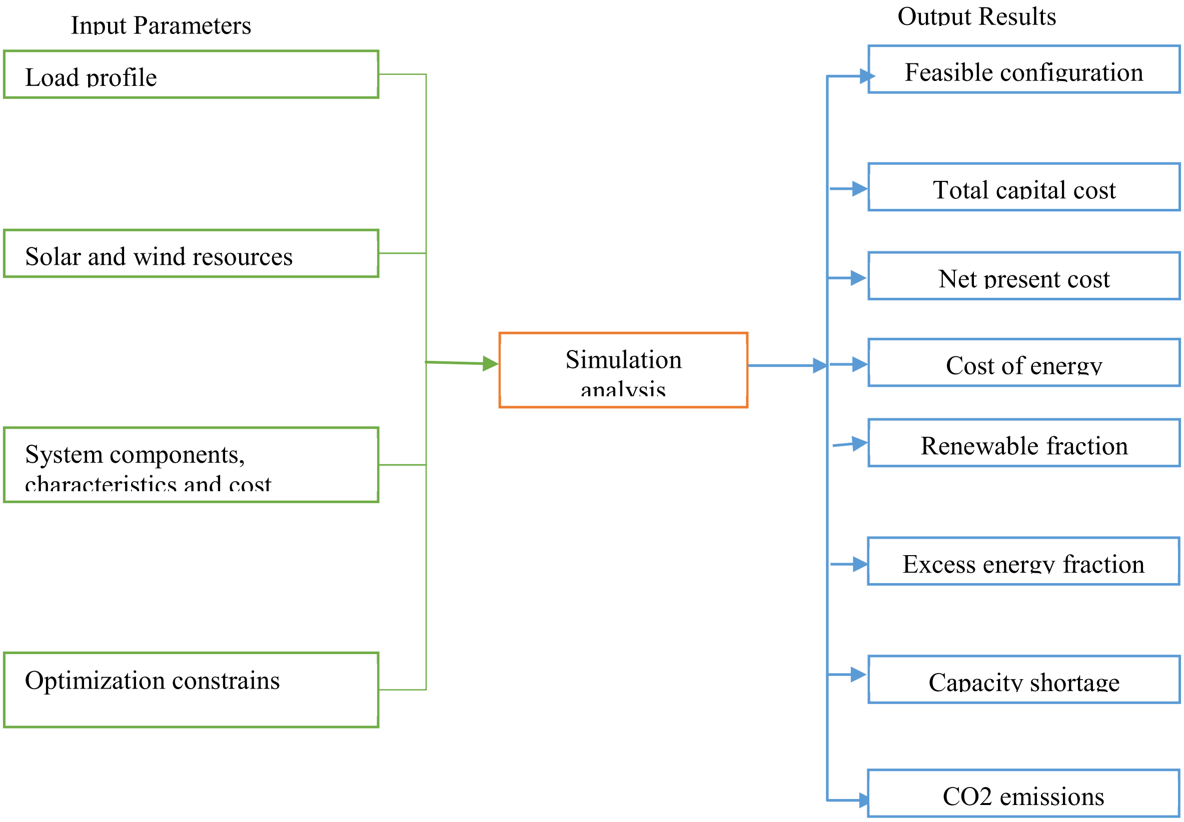

FIGURE 2. HOMER software simulation analysis process architecture diagram.

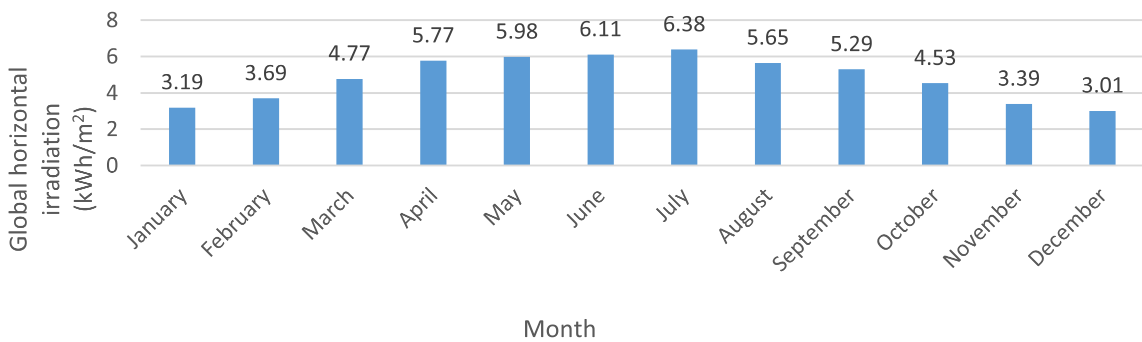

FIGURE 3. Global horizontal irradiation-monthly data of the selected area.

operate in parallel because of poor power quality. To improve the quality of power supply on the island, and consider the environmental conservation issues of the National Ocean Park, the study analyzes the electrical and techno-economic analysis of the hybrid power supply system depending on load demand and environmental situations on the island.

B. SIMULATION SOFTWARE DESCRIPTION

HOMER software is industrialized by NREL (National Renewable Energy Laboratory). The software is helpful to analyze electricity and economic of power system so as to model optimal power grid. Moreover, users can also specify the input parameters and constraints as a guide for modeling the economic power system [42], [43]. HOMER software simulation analysis process architecture diagram is shown in fig. 2.

C. GLOBAL HORIZONTAL IRRADIATION

Input latitude and longitude of the Pratas island in the HOMER software to obtain NASA's GHI data statistics via the Internet. The annual GHI is 1756 kWh/m2/year, and the daily average GHI is 4.81 kWh/m2/day. As shown in fig. 3, change of daily average GHI for each month varies from 3.01 kWh/m2/day to 6.38 kWh/m2/day. The monthly average

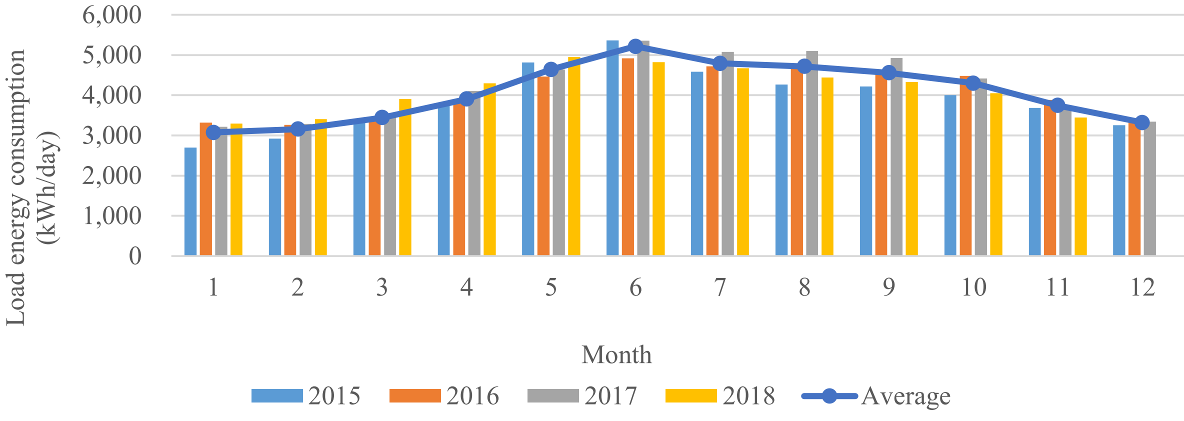

FIGURE 4. Monthly energy consumption.

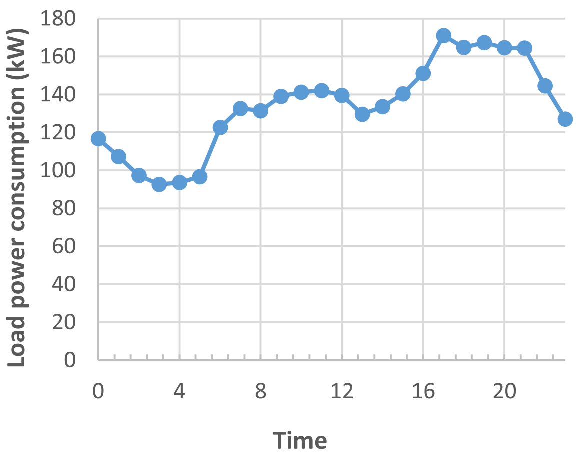

FIGURE 5. Typical daily load profile.

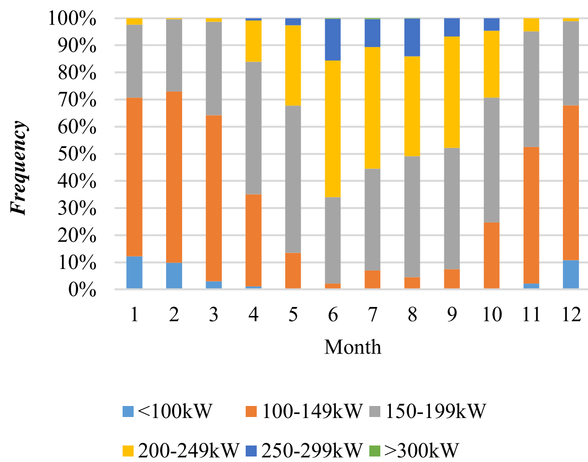

FIGURE 6. Load power consumption frequency distribution per month.

GHI exceeds 6 kWh/m2/day in June and July, and the highest GHI is in July. The daily average of GHI is lower than 4 kWh/m2/day from November to January, and the lowest GHI is in December. The detailed environmental climate data of the study area are presented in Table 11 of the appendix.

D. LOAD PROFILE

Through the investigation, load profile and distribution of the power level, the period of statistic was from January 2015 to November 2018, totally 47 months. As presented in fig. 4, the difference of each month is because of load demand for electricity related to marine research, engineering facilities, and activities. The air-conditioning is the main load. On average the power consumption is 4,076 kWh/day, and June to September having high electricity consumption. The statistics of daily loading is depicted in fig. 5. The Maximum load consumption is at 17:00-21:00, the load power is about 200kW, and the difference between peak and off-peak is about 74kW. Fig. 6 shows load power consumption frequency distribution per month.

As the load power consumption increases, the frequency of occurrence above 200 kW is higher. Take June, which has the highest load power consumption as an example, the frequency of occurrence of load power above 200kW is 65.98% on condition that the sampling period is hourly. The frequency of occurrence from 200 kW to 249 kW is 50.42%, from 250 kW to 299 kW is 15.28%, and for 300 kW is 0.28%. The frequency of occurrence above 200 kW is only 2.42% in January. Fig. 7 indicates power consumption frequency of occurrence for statistics of 47 months. Frequency of occurrence in the range of 100 kW to 199 kW is highest and the proportion is 70.95%. The highest load power consumption is 313 kW.

E. PV SYSTEM POWER GENERATION PERFORMANCE

In July 2015, the 40kWp PV system was built on the island. The PV system was operated in parallel with the diesel generator set and started in January 2016. However, the PV inverter has failed to operate in parallel many times because of power quality of the diesel generator set and maintenance of the generator. Fig. 8 shows that the average daily power generation per kWp in 35 months was only 3.27 kWh/kWp/day,

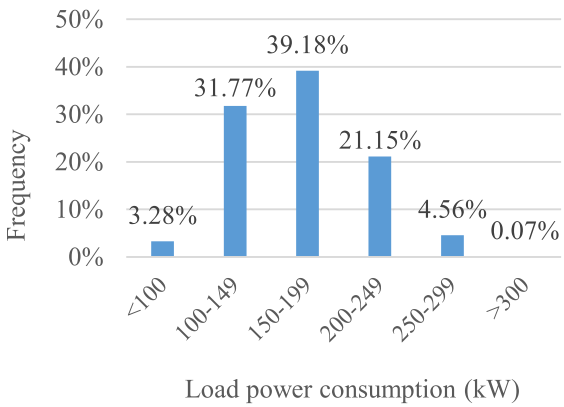

FIGURE 7. Load power consumption frequency distribution.

FIGURE 9. Diesel fuel price data.

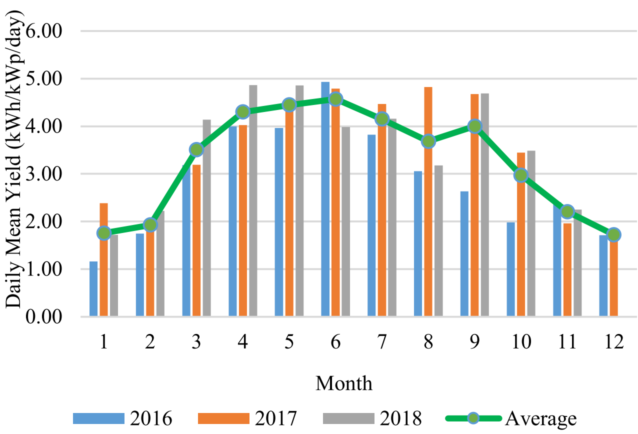

FIGURE 8. Daily mean yield of PV system.

which is lower than the 3.82 kWh/kWp/day estimated by PV simulation software before construction. According to statistical analysis, the proportion of PV power generation to load power consumption was 2.92% in 2016, 3.41% in 2017, 3.58% in 2018, and the average is 3.3%. The results also indicate that the proportion of diesel generators reduces the output power.

F. DIESEL PRICE DATA

Fig. 9 [44] shows that the distribution of diesel fuel price for the past 5 years from Chinese Petroleum Corporation. Because Taiwan's diesel price is adjusted with fluctuations in international diesel prices, the highest diesel retail price was 33.5 NTD/Liter, the lowest was 15.5 NTD/liter, and the average was 23.93 NTD/liter, equivalent to US dollars 0.78 \$/liter (1\$=30.55 NTD) for the statistical duration since January 2014 to December 2018. The price of diesel in the off shore island must add to the transportation and management costs. Therefore, through the investigation, the cost of diesel purchases in Dongsha Island is about 1.2 times of the retail price, which is 0.94 \$/liter. This paper uses the diesel price as the basic parameter to simulate.

G. ECONOMIC ASSIGNMENT CRITERIA

Annual interest rate, capital recovery factor (CRF), NPC, COE are key constraints considered in economic assignment criteria [45].

1) ANNUAL REAL INTEREST RATE

Annual real interest rate (i) is helpful to convert among one-time cost and annualized costs. HOMER uses the annual real interest rate to calculate discount factor and to execute annualized costs from present costs.

$$i = \frac{i' - f}{1 + f} \tag{1}$$

f is expected inflation rate, i' is nominal interest rate, i is annual real interest rate (%).

2) NET PRESENT COST

Total of NPC value represents the cost of system life cycle in HOMER. Equation (2) indicates the summation of the cash flow of the t-year over the factor and the initial capital cost. The costs contain capital cost, fuel cost, operation cost, replacement cost, maintenance cost, etc. Income contains electricity selling and salvage value after life cycle.

$$\begin{aligned} NPC &= CF_0 + \{\frac{CF_1}{(1+i)^1} + \frac{CF_2}{(1+i)^2} + \frac{CF_3}{(1+i)^3} + \ldots \\ &\quad + \frac{CF_N}{(1+i)^N} \\ &= CF_0 + \sum_{t=1}^{N} \frac{CF_t}{(1+i)^t} \end{aligned} \tag{2}$$

CF_0 is the initial capital cost (\$); CF_t is cash flow of t-year (according to HOMER software: expenditure is positive and income is negative) (\$); t is number of year (year); i is annual real interest rate (%); N is project life time (year).

3) CAPITAL RECOVERY FACTOR

Capital recovery factor (CRF) is the ratio helps to determine the present value of the annuity in the project life time.

$$RT\ (i, t) = \frac{i(1+i)^t}{(1+i)^t - 1} \tag{3}$$

i is the annual real interest rate (%); t is number of years (year).

4) COST OF ENERGY
HOMER describes the levelized COE as the average cost per kWh of useful electric energy generated by the system. It is calculated by dividing the Total Annualized Cost (TAC) by the total annualized useful electric energy production. The COE (in $/kWh). The TAC is the annualized value of NPC (in $/year).

$$TAC = NPC * CRF(i, N) \tag{4}$$

$$COE = \frac{TAC}{E_{prim}} \tag{5}$$

E_{prim} is the annualized primary served load (kWh/yr); N is the project life time (year).

H. ELECTRICAL ASSIGNMENT CRITERIA
The formulas described below are references to the definition and description of HOMER [45].

1) RENEWABLE FRACTION
Renewable fraction (RF) is the fraction of the energy delivered to the load that originated from renewable sources. The relation is as follow:

$$\mathrm{RF} = \left(1 - \frac{E_{non-ren} + H_{non-ren}}{E_{served} + H_{served}}\right) \times 100\% \tag{6}$$

$E_{non-ren}$ is the nonrenewable electrical production (kWh/ year);
$H_{non-ren}$ is the nonrenewable thermal production (kWh/ year);
E_{served} is the total electrical load served (kWh/ year); H_{served} is the total thermal load served (kWh/ year).

2) EXCESS ELECTRICITY FRACTION
Excess electricity fraction is the ratio of total excess electricity to the total electrical production.

$$\text{Excess electricity fraction} = \frac{E_{excess}}{E_{prod}} \times 100\% \tag{7}$$

E_{excess} is total excess electricity (kWh/ year); E_{prod} is total electrical production (kWh/ year).

3) CAPACITY SHORTAGE FRACTION
The capacity shortage fraction is equal to the total capacity shortage divided by the total electrical demand. The equation is as follow:

$$\text{Capacity shortage fraction} = \frac{E_{cs}}{E_{demand}} \times 100\% \tag{8}$$

E_{cs} is the total excess electricity (kWh/ year); E_{demand} is total electrical production (kWh/ year).

III. MINI-GRID HYBRID POWER SYSTEM DESCRIPTION
A. MINI-GRID HYBRID POWER SYSTEM SCHEMATIC
Schematic diagram of hybrid system is depicted in fig. 10. in daytime, the electricity generated by PV can be delivered to AC load to reduce diesel generator output and fuel intake [46], [47].

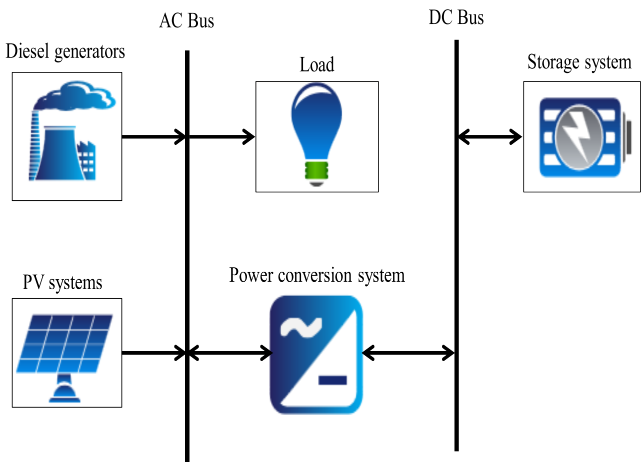

FIGURE 10. Schematic diagram of the mini-grid hybrid power.

B. PV SYSTEM
Identifying, implementing and using efficient interconnection techniques to assembly crystalline silicon solar cells in a PV module is crucial to ensure that the system achieves its expected life span continuously up to 25 years [48]. PV module selected for simulation is a GTEC-G6S6A model [49] with mono-crystalline silicon solar cell type and specifications of: 300 Wp rated power, 18.44% efficiency, 0.4007 %/°C coefficient of power temperature, south installation direction, 10° incline, 25 years working life and 80% derating factor.

C. STORAGE SYSTEM
The Storage system is used to regulate power and minimize the influence of power fluctuation on intermittent renewables in the hybrid power generation. It harvests and transfers energy from PV and diesel systems to a rechargeable thin-film Li-Ion battery when excess power is produced [50]. This research used a high energy density Samsung SDI M8194 E2 model lithium-ion battery [51] as storage with specification as follow. Minimum life expectancy of each rack is 5 years and each rack comprises 11 modules with 22 series of connected cells in each module. Capacity of a cell is 94 Ah and rated capacity for each storage rack is 83.7 kWh. The running voltage is 774∼1004 V and the lowest state of charge (SOC) is 20%. The C rate is 1C and lifetime throughout is 337,123kWh.

D. POWER CONVERSION SYSTEM
The power conversion system is a bi-directional DC-AC converter. In the hybrid energy system, when the diesel generator

and PV generate surplus power, the surplus AC power is converted into DC and stored in the battery to deliver it back to AC load later. Conversion efficiency of 95% with 10 years of working life is considered in the simulation.

E. DIESEL GENERATORS

Because there are four 500kW diesel generator sets on the island that have been in operation for more than 13 years, the maintenance is frequent, which has caused problems such as the PV system cannot operate with the diesel generator set. Therefore, this paper analyzes the suitable capacity of the new diesel generator set through the HOMER software considering the load profile. In HOMER software, input the load profile and select "Autosize Genset" for the diesel generator specification, and set the maximum annual capacity shortage fraction of the system operational constraint to 0%. The software automatically adjusts the appropriate capacity and meets the system operational constraint. After the software analysis, the single generator capacity of the diesel generator set is 330kW, which can meet the operating conditions, and the output value of the diesel generator set output per hour. According to the results of the analysis, the research uses FPT GE CURSOR400EA to meet the capacity requirements through the market survey [52]. Four generators take turns supplying power to improve the reliability of power supply system and extend its life. Simulation parameters are as depicted in table 2.

TABLE 2. Simulation parameters of diesel generator.

Brand	Rated Prime Power (kW)	Engine Type	Fuel consumption (liter/hour)	Minimum load ratio
FPT Industrial	336 at1800rpm	C13 TE3A	98.1 at full load 82.5 at 80% load 55 at 50% load	25%

F. SYSTEM DISPATCH STRATEGY

HOMER's dispatch method is mainly for handling the operating rules between power generation equipment and energy storage. The software has two alternatives: load following strategy and cycle charging strategy. The hybrid system operates with DG as the main power supply in this case. The PV system is the auxiliary power supply. Increasing PV system permeability to minimize fuel consumption, DG only generates power to meet the demand. DG has a limit output of the minimum load (base load), so when the PV system has excess power generation, it will charge the storage system or limit the output of the PV system. Hence, the dispatch approach of the system must select the following strategy to perform simulation analysis and calculate the costs of fuel, operation and maintenance, and replacement.

IV. COMPONENT COST AND FINANCIAL ANALYSIS

A. SYSTEM COMPONENT COST

Component cost for simulation analysis of this case is calculated by the Taiwan system integration company. As depicted in table 3, it is categorized into capital cost, replacement cost, operation and maintenance (O&M). The cost of the capital and replacement are the same so as to reduce analysis. The PV system capital cost is 4,200 $/kW per kW, including PV module, PV inverter, fixing hardware and other balance of system, transportation, installation engineering and others. Because PV and the storage system are run in parallel with existing 40 kWp PV system, the capital cost of 40 kWp PV system is excluded from calculation. Estimation of the cost of other components includes installation and transportation.

TABLE 3. Summary of cost of components.

Description	Data description
PV system	
Capital cost ($/kW)	4,200
Replacement cost ($/kW)	4,200
Operation and maintenance cost ($/kW/year)	10
Storage	
Capital cost ($/kWh)	690
Replacement cost ($/kWh)	690
Operation and maintenance cost ($/kWh/year)	5
Power converter	
Capital cost ($/kW)	900
Replacement cost ($/kW)	900
Operation and maintenance cost ($/kW/year)	1
Diesel generator	
Capital cost ($/kW)	465
Replacement cost ($/kW)	465
Operation and maintenance ($/h)	0.02

B. INTEREST RATE AND INFLATION RATE

As shown in fig. 11, the statistics of the interest rate announced by the Central Bank of Taiwan for the past five years. In December 2018, the one-year deposit card rate was 1.04%, the average of 5 years was 1.18 %, the highest and lowest were 1.38% and 1.04% respectively. Fig. 12 shows the inflation rate information of the Directorate General of Budget, Accounting and Statistics, Executive Yuan, R.O.C. in the past 5 years [53]. The inflation rate in December 2018 is 0.31%, the average of 5-year is 0.87%, the highest and lowest are 2.41% and -0.94% respectively. In this paper, average of the statistical period is used as the analysis parameter, and the real discount rate is 0.31% calculated by (1). The project life time in the simulation is set to 20 years.

TABLE 4. Electrical characteristics of the stand-alone diesel system.

Component	Operation schedule	Hours of Operation (hrs/year)	Electrical Production (kWh/year)	Fuel Consumption (liter/year)	Specific Fuel Consumption (liter/kWh)
DG1	AM 00-05	2,190	299,008	103,403	0.35
DG2	AM 06-11	2,190	379,063	124,205	0.33
DG3	PM 12-17	2,190	396,461	128,725	0.32
DG4	PM 18-23	2,190	413,376	133,121	0.32
System		8,760	1,487,908	489,454	0.33

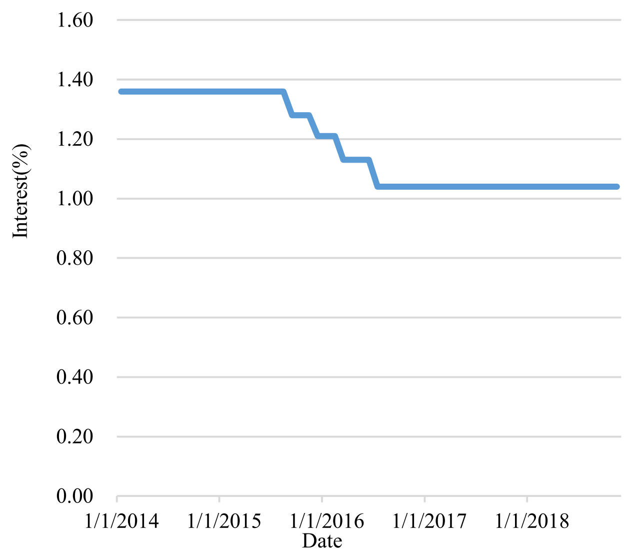

FIGURE 11. Interest rate information for the Taiwan from January 2014 to November 2018.

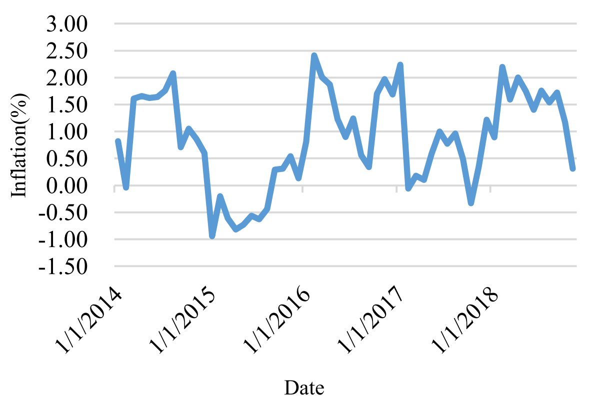

FIGURE 12. Inflation rate information for the Taiwan from January 2014 to November 2018.

V. SIMULATION RESULTS AND DISCUSSION

A. STAND-ALONE DIESEL SYSTEM

According to simulation parameter and results of HOMER analysis, as indicated in table 4, the fuel intake of four DGs is 489,454 Liter/year (1,341 Liter/day), the total annual power delivery is 1,487,908 kWh/year and fuel intake of per kWh is 0.33 Liter/kWh, and annual carbon dioxide (CO2) emissions are 1,288,893 kg/year. As depicted in fig. 13, the ratios of power supply of DG1, DG2, DG3 and DG4 are 20.1%, 25.48%, 26.65% and 27.78%, respectively. The results show that the system has no shortage of capacity throughout the year and meet annual load demand. The time of DG1 operation is at 0 to 5 a.m., and the load is relatively lower than other time periods. Therefore, the fuel consumption (L/kWh) needed per kWh is somewhat more than the other diesel generator sets.

As presented in table 5, total NPC of four DGs is \$10,284,686, and total COE is 0.3569 \$/kWh, which accounts for the most of the cost of fuel costs, which is 87% of total NPC.

B. STAND-ALONE PV/STORAGE SYSTEM

This section discusses the scenario of PV/storage system power supply, which provides hundred percent of renewable energy and meets the load demand and has no CO2 emission problem [54]. The limit conditions of capacity shortage fraction contain 0%, 5%, and 10%. In order to meet the capacity shortage fraction of 0%, it should be followed that the required PV and storage installation capacity is 3,020 kWp and 9,960.3 kWh respectively, the required high capital cost is \$19,748,607, COE is 0.6616 (\$/kWh), having enough installation space, and the excess electricity fraction raise to 54.5% as depicted in table 6. The reserved power can meet short-term power shortages. Under the condition that the capacity shortage fraction is 10%, means the annual power supply capacity is only 90% of the load demand, the capital cost and the capacity shortage fraction 0% condition are about 2 times worse, but the problem of power outage must be endured.

C. HYBRID SYSTEM SCENARIOS

1) PV/DIESEL HYBRID SYSTEM

This section analyzes the PV system capacity configuration scheme for the lowest COE of the PV/diesel hybrid system, and sets a change of PV system capacity from 0 to 360 kWp with an interval of 20 kW. According to the analysis results,

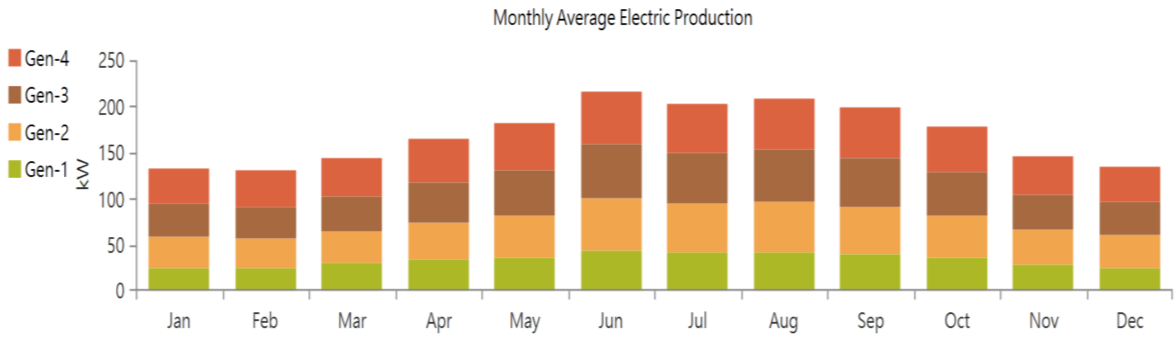

FIGURE 13. Monthly average electric production of the stand-alone diesel system.

TABLE 5. Economic characteristics of the stand-alone diesel system.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	NPC ($)	COE ($/kWh)
Gen-1	156,240	0	285,048	1,882,642	-97,960	2,225,971	0.3844
Gen-2	156,240	0	285,048	2,261,363	-97,960	2,604,692	0.3548
Gen-3	156,240	0	285,048	2,343,671	-97,960	2,686,999	0.3500
Gen-4	156,240	0	285,048	2,423,695	-97,960	2,767,023	0.3456
System	624,960	0	1,140,193	8,911,371	-391,839	10,284,686	0.3569

TABLE 6. Economic characteristics of the stand-alone PV/storage system.

Capacity Shortage Fraction (%)	**Existing PV (kWp)**	**New PV (kWp)**	**Total PV (kWp)**	**Storage (kWh)**	**Capital cost ($)**	**NPC ($)**	**COE ($/kWh)**	**Excess Electricity Fraction (%)**
0%	40	2,980	3,020	9,960.3	19,748,607	19,065,502	0.6616	54.5
5%	40	1,980	2,020	4,854.6	12,025,674	11,442,647	0.4184	35.8
10%	40	1,520	1,560	4,101.3	9,573,897	9,191,958	0.3545	21.4

TABLE 7. Electrical characteristics of the optimal size PV/diesel hybrid system.

Genset (kW)	Existing PV (kWp)	New PV (kWp)	Total PV (kWp)	Electrical Production (kWh/year)	Excess Electricity Fraction (kWh/year)	Renewable Fraction (%)	Fuel Consumption (liter/year)	Fuel saving (%)
1,344 (4 sets)	40	160	200	1,527,414	39,565 (2.6%)	15.3	430,299	-12.09

the situation is that the ESS should not be installed, as presented in fig. 14. when capacity of PV system rises, ratio of RF to fuel savings will increase, and slow down when PV system capacity rises, and the excess electricity fraction will increase.

Fig. 15 shows that COE trend in different PV system capacity configuration. When PV system size is 200kWp and the DG is operated in parallel, the minimum COE is 0.3398 $/kWh, that is relatively lower. COE (0.3569 $/kWh) in the DG-only environment, RF is 15.3%, as indicated in table 7. When PV system capacity consistently increases, investment cost will also rise. As shown in table 8, the various of cost simulation shows that the cost of fuel is still the highest among all costs, that is 80% of total NPC, and the PV system with a total capacity of 200 kWp is only 6% of the total NPC.

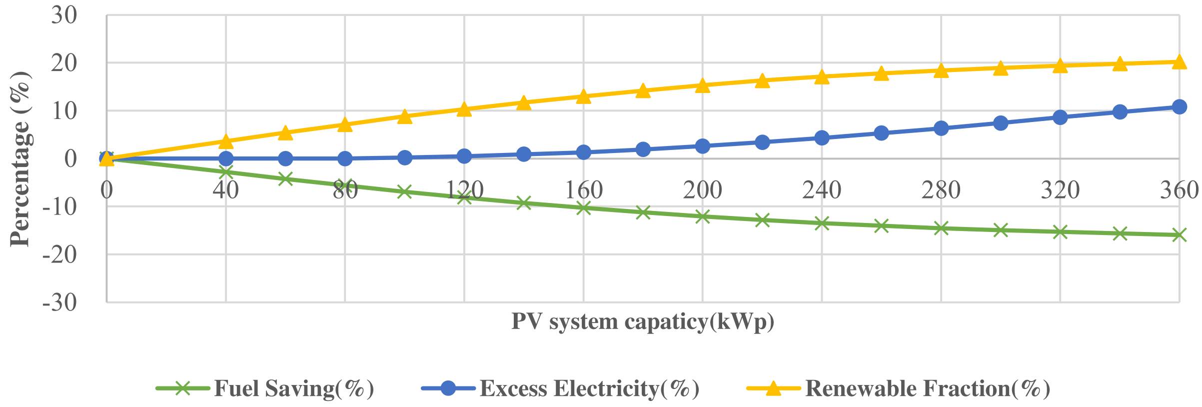

FIGURE 14. Monthly average electric production of the stand-alone diesel system.

TABLE 8. Economic characteristics of the optimal size PV/diesel hybrid system.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	NPC ($)	COE ($/kWh)
Gen-1	156,240	0	285,048	1,882,642	-97,960	2,225,971	0.3844
Gen-2	156,240	0	285,048	1,743,353	-97,960	2,086,682	0.3997
Gen-3	156,240	0	285,048	1,786,558	-97,960	2,129,886	0.3946
Gen-4	156,240	0	285,048	2,421,806	-97,960	2,765,134	0.3457
Existing PV	0	0	7,748	0	0	7,748	0.0075
New PV	672,000	0	30,990	0	-126,400	576,591	0.1391
System	1,296,960	0	1,178,931	7,834,360	-518,239	9,792,012	0.3398

TABLE 9. Electrical characteristics of the PV/diesel/storage hybrid system with different capacities.

Renewable Fraction (%)	Genset (kW)	Existing PV (kWp)	New PV (kWp)	Total PV (kWp)	Storage (kWh)	Excess Electricity Fraction (%)	Fuel Consumption (liter/day)	Fuel Saving (%)
10	1,344 (4 sets)	40	80	120	83.7	0.1	448,482	-8.37
15		40	140	180	167.4	0.5	430,369	-12.07
20		40	240	280	167.4	3.6	409,947	-16.24
25		40	300	340	502.2	2.6	391,202	-20.07
30		40	380	420	753.3	3.6	373,263	-23.74
35		40	460	500	1,171.8	3.5	352,923	-27.89
40		40	520	560	2,343.6	2.4	334,624	-31.63
45		40	620	660	5,356.8	4.2	315,460	-35.55

2) PV/DIESEL/STORAGE HYBRID SYSTEM

As depicted in fig. 15, PV system capacity rises and RF will increases, but excess electricity fraction also increases and wasting energy. The problem can be mitigated by installing an ESS. This section will discuss RF 10% - 45%, the interval is 5%, and excess electricity fraction is less than 5% of minimum COE system capacity configuration in the PV/diesel/storage hybrid system. Table 9 shows electrical characteristics of PV/diesel/storage hybrid system. The minimum COE hybrid system configuration of each RF meets that the excess electricity fraction is lower than 5%. The higher the RF, the better the effect on fuel saving. Table 10 shows the economic characteristics of PV/diesel/storage hybrid system. The table refers that RF is 20% in hybrid system configuration: PV system capacity is 280kWp, energy storage capacity is 167.4kWh and DG operates in parallel and the results can

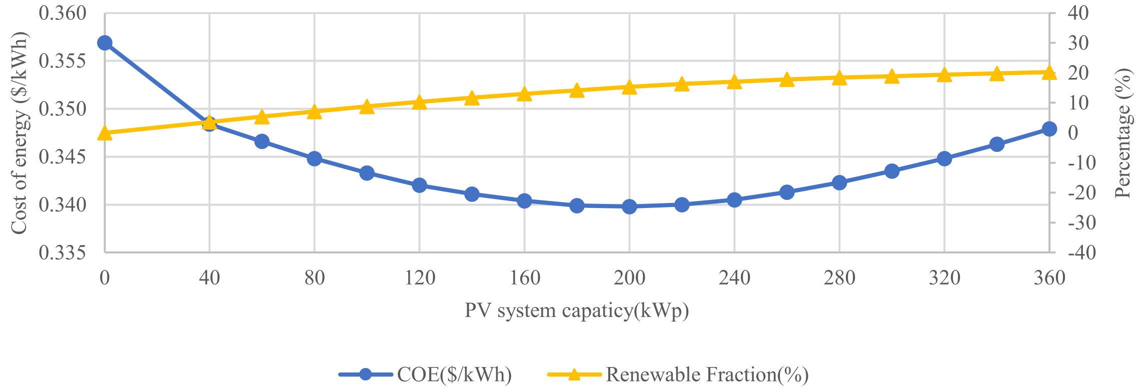

FIGURE 15. Effect of variation of PV system capacity on the COE and RF.

TABLE 10. Economic characteristics of the PV/diesel/storage hybrid system with different capacities.

Renewable Fraction (%)	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	NPC ($)	COE ($/kWh)
10	1,378,713	343,805	1,171,571	8,165,406	-680,753	10,378,742	0.3601
15	1,688,466	343,805	1,191,327	7,835,634	-728,153	10,331,080	0.3585
20	2,108,466	452,484	1,210,696	7,463,814	-914,991	10,320,469	0.3581
25	2,591,478	343,805	1,254,857	7,122,518	-854,553	10,458,106	0.3629
30	3,100,737	832,843	1,294,757	6,795,917	-1,403,303	10,620,951	0.3686
35	3,725,502	343,805	1,350,927	6,425,589	-980,952	10,864,871	0.377
40	4,786,044	343,805	1,476,438	6,092,420	-1,028,352	11,670,355	0.405
45	7,285,152	343,805	1,788,664	5,743,507	-1,107,352	14,053,777	0.4877

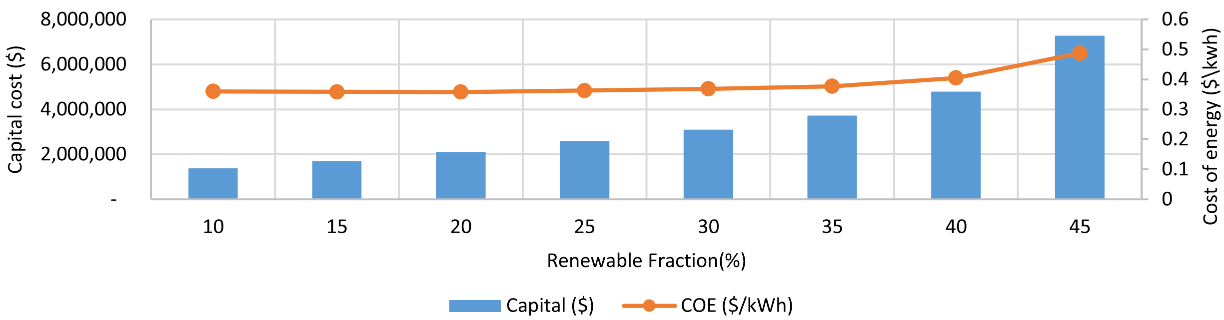

FIGURE 16. Capital cost versus COE in different RF.

be obtained that the smallest COE is 0.3581 $/kWh and NPC is $10,320,469. Fig. 16 shows the capital cost and COE in different RF. If the system wants to reach RF 45%, the capacity storage needs to be enough. The different of investment cost is 1.52 times, and the installation space is required. Therefore, if selecting the RF as the PV/diesel/storage hybrid system, the PV system capacity is 560 kWp and the energy storage capacity is 2,343.6 kWh in parallel with the DG under the condition of 40% RF. Take the RF 40% hybrid system as an example much PV system energy can be stored through the energy storage system. The excess electricity fraction can be reduced to 2.4%, and the annual total CO2 emissions are 881,175 kg/year, this is 31.63% lower than the DG-only system but with the same fuel saving ratio.

D. SENSITIVITY ANALYSIS

Based on the analysis outcome of section C, the change of GHI, load consumption, diesel fuel price, real interest rate, capital cost in RF 40% PV/diesel/storage hybrid

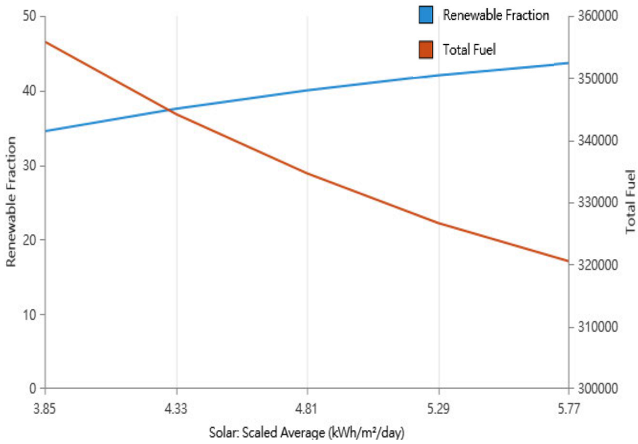

FIGURE 17. Effect of variation of GHI on RF and total fuel.

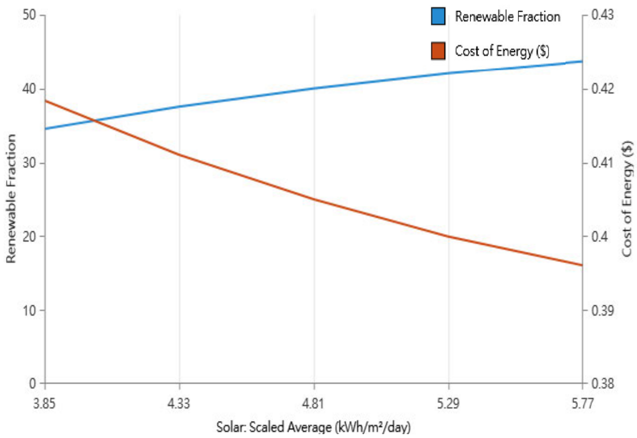

FIGURE 18. Effect of variation of GHI on the RF and COE.

system to discuss degree of influence of economic, electricity, CO2 emissions for the system.

1) GLOBAL HORIZONTAL IRRADIATION AND DIESEL FUEL PRICE DATA

Variation of GHI is ±20% of 4.81 kW/m^2/day, from 3.85 to 5.77 kW/m^2/day. When the GHI increases, the RF will continuously rise and fuel intake of DG will decrease, and COE and CO^2 emissions will also decrease, as indicated in fig. 17 to fig. 19.

When GHI is 5.77 kW/m2/day, RF increases to 43.7%, COE decreases to 0.396 $/kWh, and CO2 emissions minimized to 844,007 kg/year.

Fig. 20 is the result of changing GHI and diesel fuel price on COE generated by PV/diesel/storage hybrid system. Diesel fuel price varies from 0.6-1.3 $/liter, that is 1.2 times the highest and lowest values during diesel price statistics period.

Through this analysis, the impact of different GHI and the changes of diesel fuel price on COE can be known.

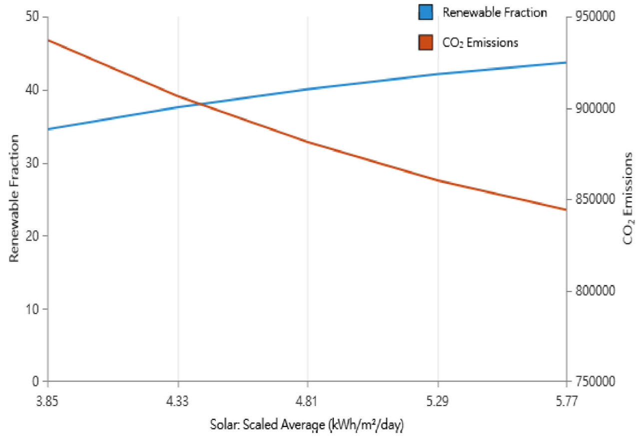

FIGURE 19. Effect of variation of GHI on the RF and CO2 emissions.

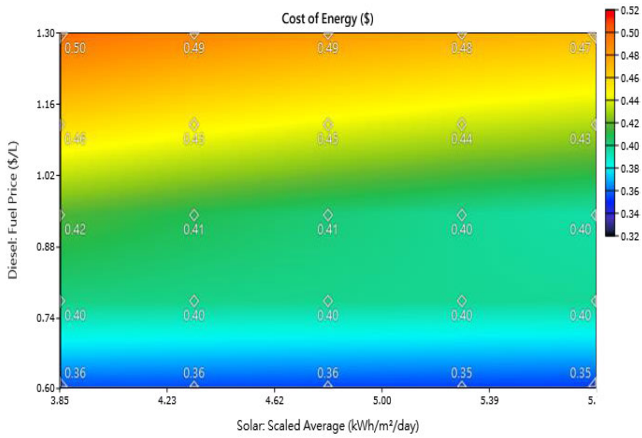

FIGURE 20. Effect of variation of GHI and diesel fuel price on COE generated by PV/diesel/storage hybrid system.

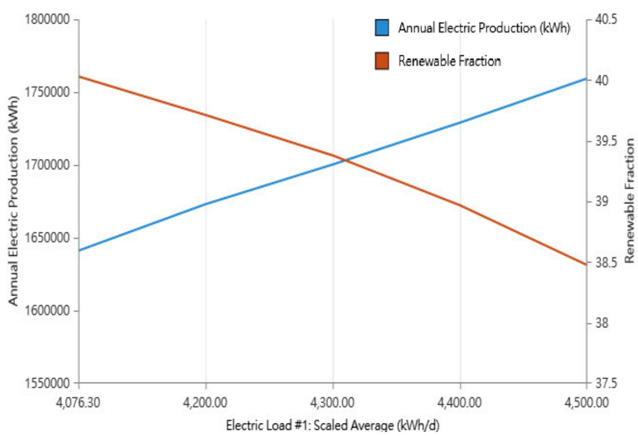

FIGURE 21. Effect of variation of load consumption on the annual electric production and RF.

2) LOAD CONSUMPTION

Set the consumption of the load from 4,076 to 4,500 kWh/day. As indicated in fig. 21, as loading increases and the storage system have the same configuration capacity, the DG will

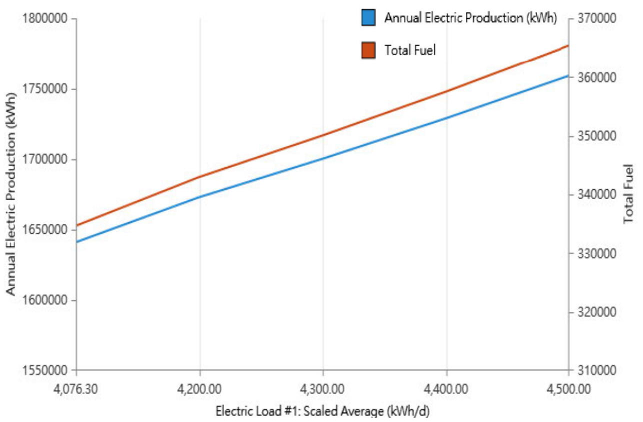

FIGURE 22. Effect of variation of load consumption on the annual electric production and fuel consumption.

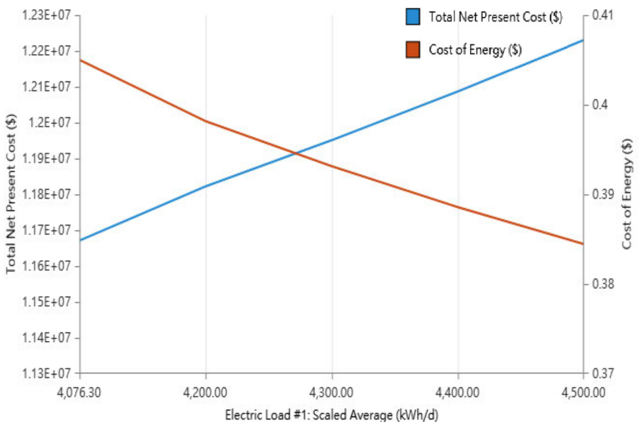

FIGURE 23. Effect of variation of load consumption on the NPC and COE.

increase the power generation to fulfill the demand and RF will be reduced. As shown in fig. 22 and fig. 23, when loading increases, fuel consumption increases as DG power generation, fuel cost increases and NPC increases. For COE, the load consumption increases and the COE decrease, as shown in (5).

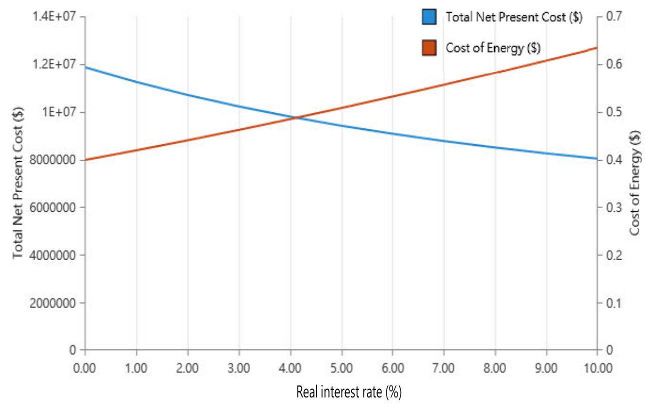

FIGURE 24. Effect of varying real interest rate on the NPC and COE.

3) REAL INTEREST RATE

Set the variation in real interest rate from 0% to 10%, with a increments of 1% to understand the effect of variation of real interest rates on NPC and COE. It can be seen from fig. 24 or equations (3-5) that as the real interest rate increases, NPC decreases and COE increases. Under the simulated setting conditions of this paper, as real interest rate increases from 0% to 10%, the NPC is comparatively decreased by 32.29%, COE is increased by 59.06%, and the COE change is greater than NPC. Real interest rate is linear with COE. For every 1% increase in real interest rate, the COE increases by an average of 0.0236 $/kWh. The long-term low interest rate environment in Taiwan has a positive impact on COE.

4) CAPITAL COST OF KEY COMPONENTS

Changing the capital cost ratio of PV system, storage system and power converter from 1 to 0.5 times, and use 10% for each interval to know the impact on COE under different PV system, storage and power converter capital cost conditions. As shown in fig. 25, under the same rate of decline, effect of reducing PV system cost on COE is greater than cost reduction of storage system and power converter. The storage

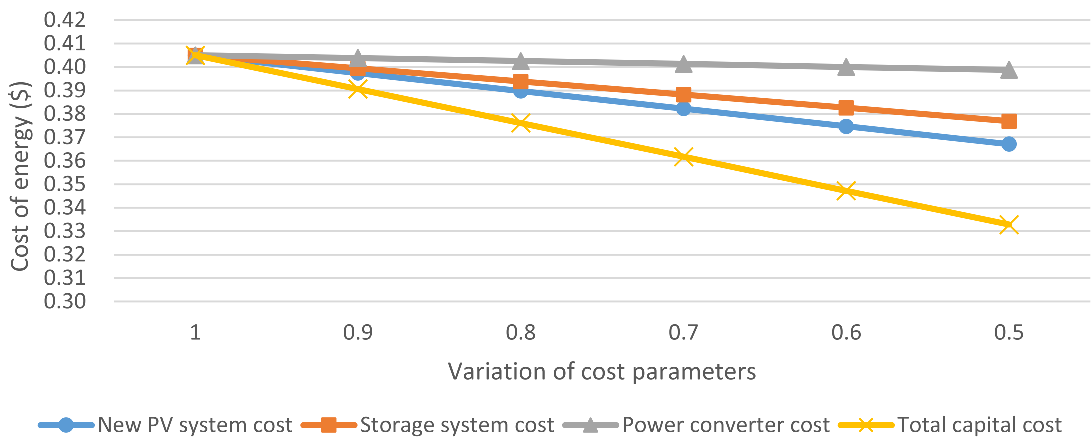

FIGURE 25. Effect of varying key components cost on the COE.

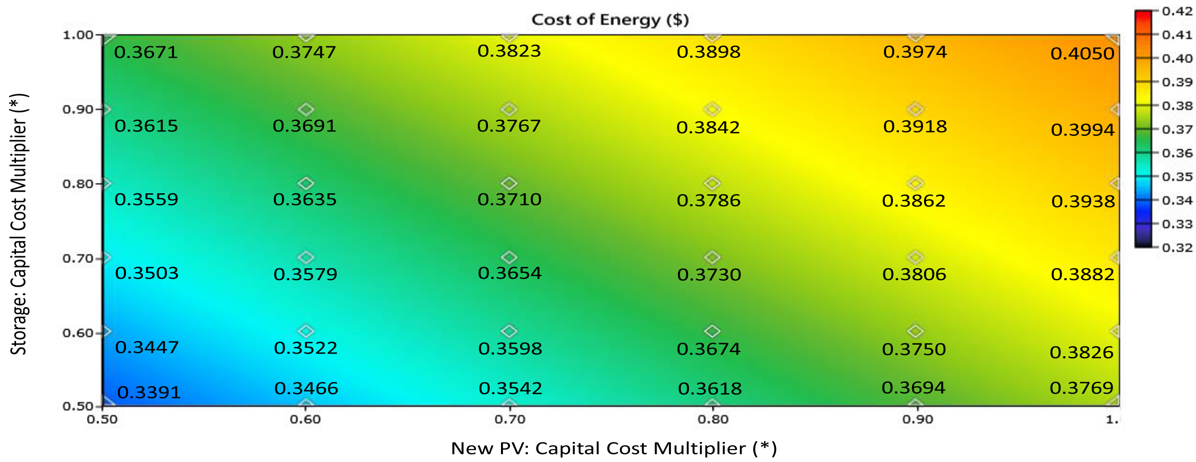

FIGURE 26. Effect of variation of PV system and storage system capital cost on COE generated by PV/diesel/storage hybrid system.

system cost reduction has a higher impact on the COE than the power converter cost reduction.

If the total cost is reduced by 0.6 times, it can be lower than the COE of 0.3569 $/kWh (DG only power supply situation).

As shown in fig. 26, When the PV system and storage system's capital costs are decreased by 0.7 and 0.5 times, 0.6 and 0.6 times, or 0.5 times and 0.8, respectively, the COE can be lower than 0.3569 $/kWh.

VI. CONCLUSION

According to the analysis of case study; stand-alone diesel, stand-alone PV/storage, PV/diesel hybrid, PV/diesel/storage hybrid systems are simulated by HOMER and the results are crucial to discuss the Techno-economic issue and the configuration scheme of capacity. The results enabled us to conclude as follows:

According to the load demand on the island, the suitable capacity of diesel generator was analyzed through the HOMER software. In the DG-only power supply environment, the COE is 0.3569 $/kWh, the annual fuel consumption is 489,454 (Liter/year) and the CO2 emissions are 1,288,893 kg/year.

Considering load demand and irradiation situations on the island, the simulation analyzes the capacity allocation and cost for the lowest COE in the PV/storage system that satisfying 0%, 5% and 10% capacity shortage fraction, respectively. From the analysis of results, the COE of the capacity shortage fraction of 0% is 0.6616 ($/kWh) and the excess electricity fraction is 54.5%. The reserved power is needed to meet short-term power shortages. Because of the extra expenditure of the equipment, the cost is 2 times that of capacity shortage fraction 10%. Compared with other schemes, the PV/storage system scheme has the highest COE, but no CO2 emissions, air and noise pollution problems.

Through the investigation of PV/diesel hybrid system without energy storage, the results can be known as follows: when capacity of the PV system increases from 0- 360kWp, RF and fuel saving increase and the excess electricity fraction also increase, resulting in waste of energy. From simulation results, the minimum COE is 0.3569 $/kWh that can be found at the PV/diesel hybrid system configuration scheme with a total PV system capacity of 200 kWp, the RF is 15.3% and the excess electricity fraction is 2.6%, which is lower than the generally acceptable 5%. The fuel saving is 12.09% relative to fuel intake of stand-alone diesel system, and the ratio for reducing CO2 emissions is same as fuel saving.

Through adding an energy storage unit, hybrid power systems can improve the excess electricity fraction and increase RF. PV/diesel/storage hybrid system was also analyzed. The results show that the energy storage capacity is 167.4 kWh and the DG is operated in parallel, the minimum COE is 0.3581 $/kWh and the NPC is $10,320,469 when the total capacity of PV system is 280 kWp. The result of the case is slightly higher than the minimum COE solution for stand-alone diesel and PV/diesel hybrid systems. If a high RF to be selected for the PV/diesel/storage hybrid system scheme, the total PV system capacity is 560 kWp and the energy storage capacity is 2,343.6 kWh in parallel with the DG under the RF 40% condition, which is a more suitable solution and the COE is 0.405 $/kWh and NPC is $11,670,355.

RF 40% was used to analyze the sensitivity in PV/diesel/storage hybrid system. As GHI increases, RF continuously increases, fuel consumption and CO2 emissions for the DG also decrease. The cost of fuel intake is the maximum amount of all costs, therefore the variation in the price of diesel has a major influence on COE. As load demand increases, DG will increasingly generate the amount of power and let to fulfill the load demand. Therefore, the NPC increases because of the decrease of RF and increase of the fuel consumption increases. As real interest rate rises, it can be known from the analysis that the NPC will decrease, and the COE is the opposite. For the long-term low interest rate of Taiwan environment, it has a positive impact on COE. Capital

TABLE 11. Environmental climate data of the study area.

Environmental climate data	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Average
Global horizontal irradiation (kWh/m2/day)	3.19	3.69	4.77	5.77	5.98	6.11	6.38	5.65	5.29	4.53	3.39	3.01	4.81
Wind speed (m/s)	9.39	7.92	6.69	5.7	5.11	6.08	5.83	5.58	6.04	9.1	10.33	10.17	7.33
Ambient temperature (°C)	21.83	22.12	23.24	24.77	26.12	26.75	26.78	26.77	26.85	26.54	24.85	22.81	24.95

cost of PV system and storage system has a significant effect on NPC and COE and is a positive correlation. The PV system cost reduction has a greater effect on the COE than storage system cost reduction. When the total capital cost of RF 40% PV/diesel/storage hybrid is reduced by 0.6 times, the COE will be lower than the diesel system. Although the COE of PV/diesel/storage hybrid is higher than that of stand-alone diesel system, the annual total CO_2 emissions is reduced by 31.63%, which is of great benefit to environmental protection.

APPENDIX

See Table 11.

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