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Optimal Design for Hybrid Renewable Energy System Using Particle Swarm Optimization

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Abstract- This paper proposes the Particle Swarm Optimization (PSO) to minimize the Hybrid Renewable Energy System (HRES) Cost of Energy (COE) on different sizing between wind turbines and solar PV modules subjecting to a particular investment constraint. The wind speed and solar irradiation data from a particular site are used to determine the annual energy production (AEP) following the HRES configuration. While the turbine power curve converts the wind speed range to wind power, solar power generation model transforms solar radiation incident on PV modules. The investment cost of the solar PV system is interpolated from a commercial supplier data. However, the wind turbine cost is derived from the turbine component cost model of the National Renewable Energy Laboratory (NREL) and discounted to the present value using the inflation rate. Once a wind turbine and PV modules are configured as HRES, the COE as the objective function would be determined. The minimum COE from this study at 0.1204 $/kWh is in the 95th percentile of the global renewable power generation cost database from IRENA ranging between 0.06 – 0.22 $/kWh for solar energy and 0.04 – 0.10 $/kWh for wind energy but higher than the average value because of the low potential on both solar radiation and wind speed data from the particular site. However, PSO as the preliminary design method could be determined the optimal HRES with minimized COE when compare with the conventional design.

Keywords Hybrid Renewable Energy System, Solar Energy, Wind Energy, Particle Swarm Optimization.

1. Introduction

Renewable energy is the energy collected from the natural source and capable to regenerate within a short period. It could originate both directly and indirectly from the sun causing the natural movement or environment transform. Solar and wind energy as renewable energy could provide a high potential in electrical energy production because of available technology on commercial and economical investment proof. Moreover, many countries provide the various incentives to promote the utilization of both solar and wind energy to meet the stability of the energy capacity performance and indirectly affect the low carbon society including social behavior and awareness.

However, the uncertainty of the single renewable source decreases in the utilized reliability leading to the redundant system design and the need to install the amount of battery storage for the unavailable source period. For this reason, the Hybrid Renewable Energy System (HRES) is developed by integrating between the different renewable energy and the conventional source to stability, flexibility and reliability system as shown in Figure 1. The system could be configured into stand-alone with the storage unit or grid connection leading to decrease on both capital investment and cost of energy when compared with only single renewable source [1].

The conventional system design chooses the HRES configuration based on the average wind and solar information or the worst scenario data leading to the excessive system causing oversize neither wind turbine nor solar PV capacity. This situation rarely appears and unsteady caused by the long period of time-series data collection with the inconsistency of weather conditions and electrical demand. Moreover, the objective function directly deals with the algorithm. Therefore, the solution for optimal configuration would combine with both linear and non-linear characteristics which are difficult to meet the global optimal. Much research have been studied the various method to design the system.

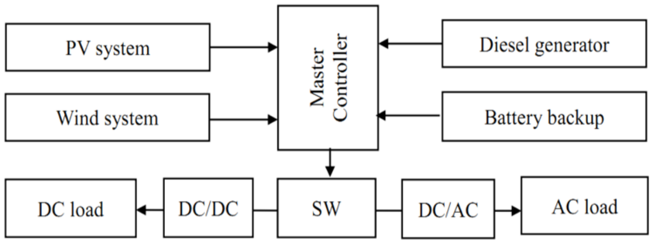

Fig.1 The generalized HRES schematic

P. Bajpai and V. Dash [2] develope the generalized model of HRES used to choose the strategy for information control and energy flow management. They classify the HRES sizing methods based on available weather data. The conventional technique including the energy balance method and reliability of the supply method are used when the long term meteorological data available which could not collect in many remote areas. For the non-availability data area, Artificial Intelligence (AI) techniques could be implemented to search for optimal sizing including Neural Networks (ANN), Fuzzy Logic (FL), Genetic Algorithms (GA) or a hybrid of such technique. These methods provide approximate results depending on diversifying the search. P.Nema et al. [3] showed the system design development for the rural area should be improved including the performance, accurate energy reserve and reliability. The pre-feasibility design strongly depends on available weather data at the site both solar insolation and wind speed. Then, the unit sizing of the integrated power system plays an important role in deciding the reliability and economy of the system. Various optimization techniques including linear programming, iterative technique and metaheuristic algorithm or intelligent optimization were used to search for the most cost effective enegy production [4-6]. The HRES components modeling was developed including a photovoltaic system, wind energy system and the criteria for HRES selection including loss of load probability and cost analysis [7, 8]. They conclude that to penetrate the renewable energy in power generation capacity needs to integrate HRES in the conventional network system.

For algorithms development, R.Luna-Rubio et al. [9] collected the various HRES design procedure and classified into different system architectures. They presented the appropriated algorithms into the probabilistic and analytical procedure with the compatible objective function, boundary and constraints. W. Zhou et al. [10] collected the design procedure for stand-alone HRES as the currently application. To validate the system, the algorithm was compared to the commercial software including HOMER of NREL, HOGA based on Genetic Algorithms and the spreadsheet software. Mostly commercial software focused on the economical return [11]. Therefore, the algorithm design including the graphic process, the probability and the numerical iterative should be consideration in order to diversification the objective function, boundary and constraints.

For the system with multi-objective function, A. Kaabeche et al. [12] proposed the iterative technique in order to define the HRES sizing with storage battery by changing the component sizing in each iteration. The multi-objective function required the deficiency of power supply probability (DPSP) and the levelized unit electricity cost (LUEC) using the time-series data from the Center for Renewable Development, Nigeria. M.Fadaee and M.A.M. Radzi [13] collected the stand alone HRES design using Evolutionary algorithms the multi-objective (MOEA) considering location, sizing, and systems controller. Moreover, the algorithm showed the MOEA can determine the problem with sensitivity to various energy demand situations. They found that GA and PSO appropriated capable to provide least square error in the solution. J.L. Bernal-Agustin and R. Dufo-Lopez [14] describe the comparative optimal HRES design from the commercial software with the different multi-objective in different system.

To prove the algorithm, H. Yang et al.[15] firstly proposed the HRES design method including wind turbine, solar PV module and battery storage using the genetic algorithm based on time series data. The solution showed the selected system sizing for load requirement in order to minimize the annualized cost at the telecommunication station case study. The system would be followed by keep the loss of power supply probability (LPSP). Secondly, H. Yang et al [16] constructed the HRES to serve the telecommunicated station in the coaster area in China. The system capacity at 1500W includes 2 of 6 kW wind turbines and 78 PV modules with 500Ah battery storage. One-year period collection data showed the performance of system satisfied the load requirement.

Therefore, the HRES design mainly depends on the sizing of optimal components leading to feasibility on both technology, economy and promoted the policy to launch the system into the energy market. This combination of optimal design is to choose the optimal components from the possibility depending on the objective function with specific boundaries and constraints. Beside, the more system complexity depends on the behavior of components, which can be both linear and non-linear characteristics, the uncertainty of renewable source and the design condition including continuous and discrete.

This paper proposes the optimal preliminary design for HRES sizing between solar PV modules and wind turbines based on the solar radiation data and wind speed distribution collected from the meteorological site at Naresuan University, the central of Thailand. Using solar PV generated power model and wind turbine power curve, both power extraction from solar radiation and wind speed would be derived. Besides, the solar PV cost modeling from an average Thailand commercial retail price [17] and the wind turbine cost component from the National Renewable Energy Laboratory (NREL) discounted to the present value using the inflation rate [18] are used to determine the capital expenditures and operational expenditures. PSO is employed to search for the minimum HRES cost of energy (COE_h) subject to the weighting of investment constraint between solar and wind capacity.

2. Mathematical Modelling

2.1. Wind turbine power curve

Wind turbine transforms a particular wind speed into electricity by turning a mechanical shaft work and consequently drives through an electrical power generation. The wind turbine power curve shows the relationship range between wind speeds and electrical power outputs. In principle, turbine blades initially turn and generate electricity when the wind speed at the hub height is greater than a cut-in wind speed (c_i). The electrical power would be proportional rises up with the wind speed until it achieves the rated wind speed (c_r). The blade's pitch angle would be controlled to meet the constant rated power (T_R) specified as the turbine sizing. However, the more wind speed than cut-out speed (c_o), the brake system would be lock turbine turning because of preventing machine failure. This characteristic of a particular sizing of the wind turbine power curve could be found by a manufacturer field test. To simplified the model, this paper formed a power curve by implementing the power-coefficient based model by the given cut-in, rated and cut-out speed with the least root mean square error compared to other models [19, 20] as following Eq.(1)

$$P(\bar{u}_i) = \begin{cases} 0 & : \bar{u}_i < c_i \\ \frac{1}{2}\rho A_s C_p \bar{u}_i^3 & : c_i \le \bar{u}_i < c_r \\ T_R & : c_r \le \bar{u}_i \le c_o \\ 0 & : \bar{u}_i > c_o \end{cases} \qquad (1)$$

where $P(\bar{u}_i)$ is electrical power output, $\bar{u}_i$ is a wind speed at turbine hub height, ρ is air density, A_s is swept area of wind turbine and C_p is a coefficient of power defined as 0.4 [19] and T_R represents the turbine rating R kW.

The larger turbine rating generates more power and needs a higher hub height to install. In Table 1, the turbine rated power ranging from 225 to 2000 kW is represented by size index (i) from 1 to 6. The turbine technical specification including turbine rated power, rotor diameter, hub height, cut-in, rated speed, and cut-out speed are collected from manufacturer data. Because of the consistency sizing interval, all models assort from the Vestas series except model W1250 which from Shanghai Electric Wind Power [21]. The particular turbine power curves present in Figure 2. Additional, the wind turbine cost could be found by using the National Renewable Energy Laboratory (NREL)'s component cost model as in [22].

The wind speed data generally collect from a particular height could not provide all sizes of wind turbines. At the different hub height, the wind power law is used to the model of vertical wind speed profile as following,

$$\bar{u}_H = \bar{u}_{ref}\left(\frac{H}{H_{ref}}\right)^{\alpha} \qquad (2)$$

where $\bar{u}_H$ is the hub height (H) wind speed, $\bar{u}_{ref}$ is the recorded wind speed at the reference height (H_{ref}) and α is the wind speed power law coefficient defined as 1/7 for the low roughness surfaces.

Table 1. The characteristic of wind turbine series

Index (i)	1	2	3	4	5	6
model	V29	V47	V60	W1250	V82	V90
T_{Ri} (kW)	225	660	900	1,250	1,650	2,000
Rotor(m)	29	47	60	70	82	90
Hub (m)	31	50	60	70	80	90
c_i (m/s)	3	3.5	3.5	3.5	3.5	3.5
c_r (m/s)	13	14	15	15	15	15
c_o (m/s)	20	25	25	25	25	25
A_s (m^2)	661	1,735	2,827	3,848	5,281	6,362
Cost (M$)	0.302	0.762	1.124	1.576	2.132	2.741
Cost/kW ($/kW)	1,345	1,155	1,249	1,261	1,292	1,371

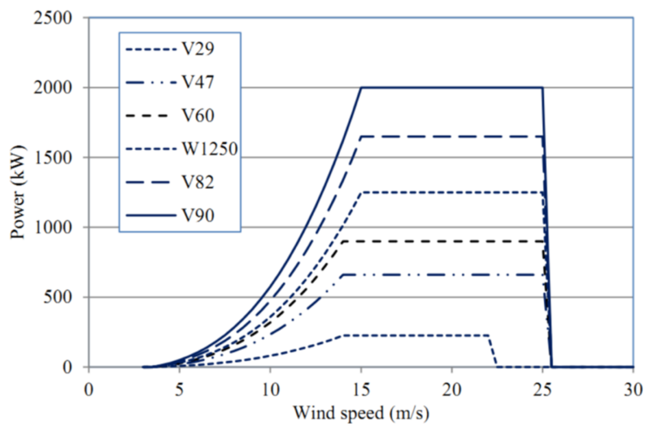

Fig. 2 The series of wind turbine power curve model following Eq.(1)

The average annual power generation (P_w as kW) represents the constant power output from the wind turbine determined from the accumulation product of particular turbine power from Eq.(1) and its frequency wind distribution within the range of wind speed around the site as:

$$P_w = \sum_{i=c_i}^{c_o} f_i P(\bar{u}_i) \qquad (3)$$

where f_i is the wind probability distribution at speed i m/s as shown in Figure 6. Therefore, the annual energy production from the wind turbine (AEP_w) obtains by Eq.(4) :

$$AEP_w = P_w \times 24 \times 365 \qquad (4)$$

Additional, the wind capacity factor (CF_w) for the particular site is determined from the following relation:

$$CF_w = \frac{AEP_w}{T_R \times 8760} = \frac{P_w}{T_R} \tag{5}$$

2.2. Wind turbine cost model

National Renewable Energy Laboratory (NREL) proposes a component cost model of wind turbine and its implementation cost based on a spreadsheet scaling model using the regression between component weight and manufacture cost for the different turbine sizing. The total capital expenditure of wind farm ($CAPEX_w$) could be found as shown in Eq.(6) [22].

$$CAPEX_w = TCC_i + BOS_i \tag{6}$$

where TCC_i is the turbine components cost and BOS_i is the balance of station cost of wind turbine size index i.

The turbine components cost would be proportional determines from its component weight including rotor diameter, drive train and nacelle, tower height and manufacture work. This model accounts for the balance of station cost including the foundation construction, logistics, installation and assembly work, road and site assessment, control system and electrical interface and connection, engineering design, safety and permit registration cost. Moreover, this paper account for Thailand 10 years averages inflation rate as 2.5% [23] as an incremental price to the year of consideration. To determine the cost of wind energy, the model proportional treats including the operation and maintenance cost, land lease cost and replacement part as the amount of annual energy production as shown in Eq.(12).

2.3. Solar PV power assessment

The solar PV module power output mostly depends on solar radiation, weather condition, and module temperature. To estimate the solar PV power generator output, the data including solar radiation on the module surface, ambient temperature and manufacturers data of the PV module are used as the input in the simplified simulation model [24] as shown in Eq (7),

$$P_s = \eta_s A_s G_\beta \tag{7}$$

where η_s is the PV module efficiency, A_s is the total area of the PV module (m^2) and G_β is the solar radiation on the tilted plane (W/m^2) as the PV module inclined angle following the site latitude. Additional, the PV generator efficiency could be found as,

$$\eta_s = \eta_r \eta_{pc}\left[1 - \beta \times \left(T_c - T_{ref}\right)\right] \tag{8}$$

where η_r is the reference module efficiency, η_{pc} is the power conditioning efficiency generally equaling to 100% for the complete track on the maximum power point (MPPT), β is the temperature coefficient ranging 0.0004-0.0006 per ^{o}C, T_{ref} is the reference cell temperature (^{o}C) from manufacturer testing data and T_c is the cell temperature estimating from the ambient temperature (T_a) and the solar radiation (G_β) from site data logger as following,

$$T_c = T_a + \left(\frac{NOCT - 20}{800}\right) G_\beta \tag{9}$$

$NOCT$ is the normal operating cell temperature generally providing as $T_{a,NOCT}$ = 20 ^{o}C and $G_{\beta,NOCT}$ = 800 W/m^2 at 1 m/s of wind speed.

2.4. Solar PV cost model

In this paper, the solar PV cost model is derived from the PV system component cost model. The main parts and accessories cost data are collected from the commercial average price in the Thailand market. The 300W of PV module specification shown Table 2 is used in this study. The transportation and installation cost is based on the medium price from various project TOR announcing from the Department of Alternative Energy Development and Efficiency [25], Thailand Ministry of Energy and the internal publication in Thai [26-28]. The total capital expenditure per capacity power unit is shown in Figure 3. This cost model is compared with a few actual solar farm sites less than 20kW and could have a huge error in the large capacity projects. However, the improvement of the solar cost model could be modified and applied in this developed algorithm.

Table 2 Solar PV specification.

Cell type	Monocrystalline
Maximum Power (Pmax, W)	300
Module Efficiency (%)	17.5
Cell Dimensions (mm^2)	161.7 x 161.7
NOCT (^{o}C)	45
Output Warranty of Pmax	1) 1st year: 98% 2) After 1st year: 0.5%p annual degradation 3) 86% for 25 years

Note: Standard Test Condition (STC) at irradiance 1000 W/m^2, cell temperature 25 °C

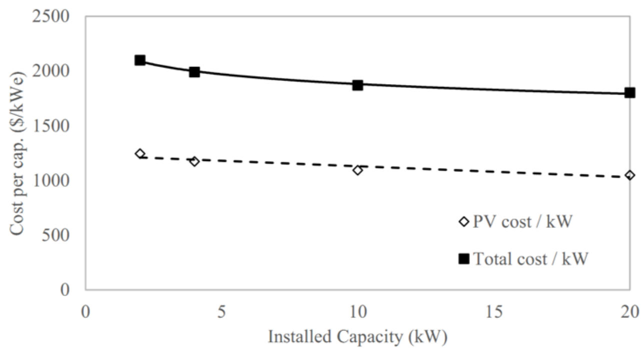

Fig. 3 the total cost of solar PV per capacity

3. Methodology

3.1. HRES configuration

In this paper, the on-grid HRES is configured with both solar PV and wind turbine as shown in Figure 4. A wind turbine converts wind speed into energy via its generator and distributes electricity through an inverter device. As the parallel system, solar PV modules likewise convert the sunlight into energy and distributes through another inverter device. The step-up transformer increases the generated electricity to high voltage and distributes it into the utility transmission line. The metering device is installed to collect the supply of electrical energy. This simplify configuration could lower the capital expenditure and O&M cost without the battery storage. Moreover, this decreases the additional cost from the replaced and eliminated cost from an amount of battery.

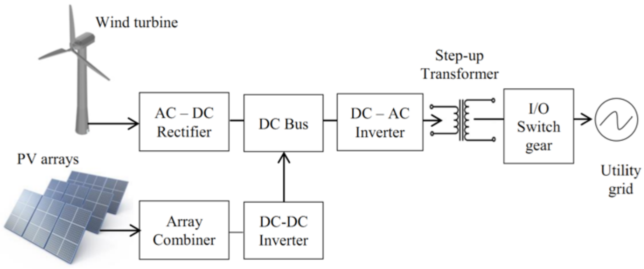

Fig. 4 the schematic diagram of the HRES preliminary design

3.2. Solar irradiation data

In this paper, 3 years of solar radiation data was collected from Naresuan University, Central of Thailand (latitude 16°44′43″N, longitude 100°11′28″E) as the studied site. Due to the Northern Hemisphere location, the monthly average global solar radiation with 15° tilted to South direction is used to determine the solar energy potential ash shown in Figure 5.

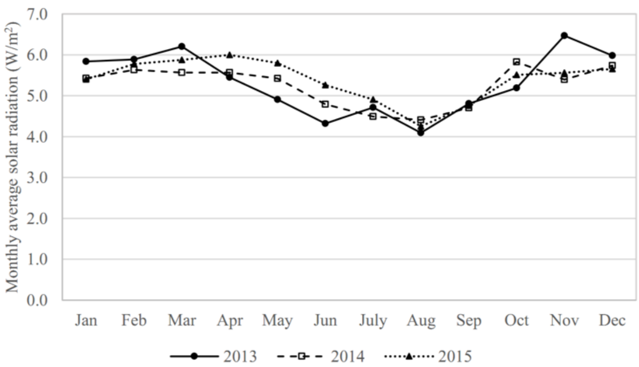

Fig. 5 the monthly average global solar radiation with 15° tilted to South direction at Naresuan University

3.3. Wind distributed data

The wind speed at Naresuan University was collected at 10 meters height, wind power law was used to find the wind speed at the turbine hub height. However, the average wind speed from this location is much lower than wind turbine rated speed as shown in Figure 6 leading to low potential in wind energy production. The search algorithm found the optimal HRES configuration without any sizing of wind turbine selection. For this reason, the data from a higher average wind speed location as Huasai district in the south of Thailand (latitude 8°04.376'N, longitude 100°27.513'E) is applied in the search procedure as shown in Figure 6. This paper uses the Hausai wind data because the Department of Alternative Energy Development and Efficiency (DEDE) already installed the pilot project wind turbine sizing 1.5MW since 2009 costing around 2420 $/kW [29] and currently plan to increase site capacity to meet the Alternative Energy Development Plan (AEDP) requirement by the year 2036 [18]. They need to compensate for the COE by other renewable sources such as solar PV. Collected wind data generally transform into the Weibull distribution and use to determine the wind energy potential. However, the actual data provides more accurate for specific site potential.

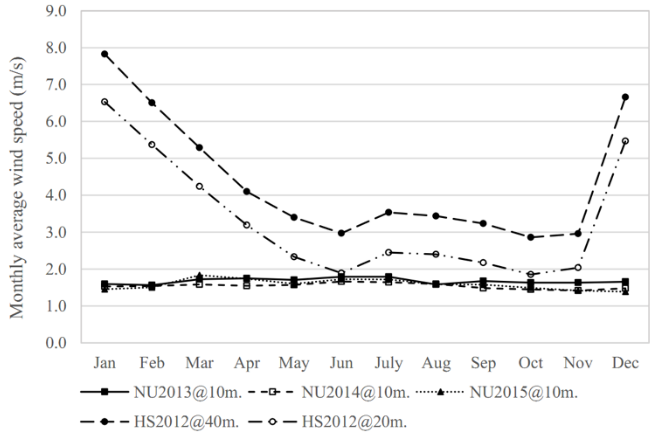

Fig. 6 the monthly average wind speed at Naresuan University (NU) and Huasai district (HS)

The location on both wind turbines and solar PV should be close to each other. This collaborated data was not appropriate in practical design but it could be used to prove the search method. However, in this paper, the algorithm has been developed to determine optimal sizing between a wind turbine and solar PV subject to investment constraint as a preliminary design. The wind speed and solar radiation should be high potential enough to apply in this developed algorithm. If any particular site provides both wind speed and solar radiation data, this PSO could be re-run and uses as a preliminary design to determine the potential sizing of HRES. Moreover, this method could be useful for a developer with a particular fund who could be considered the priority of investment between solar and wind energy in different locations. This implies that there is no limitation of data available to apply in this algorithm.

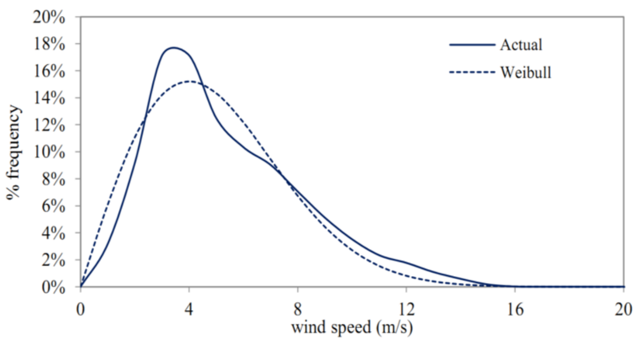

Fig. 7 The frequency of wind speed and its Weibull distribution

3.4. Particle swarm optimization (PSO)

PSO is one of the metaheuristic algorithms or the population-based stochastic search algorithm developing to search for the optimal answer based on the objectives and constraints of the complexity and multi-dimensional variables problem. The PSO concept is imitated from the group of social creatures or swarm behavior such as fish or birds. PSO emulates a population or a group of particles within the search space.

A particle (i) holds its information vectors both a current position (x_i) and velocity (v_i). While the swarm flow in the search space in each iteration, any particle would be found its best position called "Particle best ($pbest_i$)" and the swarm or group best position called "Group best ($gbest_i$)". The best position in each iteration (k) reminded as the answer value following the objective or fitness function. Both information would be exchanged within the swarm would be driving the other particle to change their position and velocity in the next iteration ($k+1$). Note that, the members of a swarm would be remains in the search process.

Following the procedure of PSO, a swarm has N particles. Each particle (x_1, x_2... x_N) in k iteration denoted as x_i^k would hold its velocity v_i^k. Each particle best denoted as $pbest_i^k$ is the best fitness value than the previous iteration. If the next best group fitness value is not better than the previous one, then $pbest_i^{k+1}$ is equal to $pbest_i^k$. While the swarm or group best denoted as $gbest_i^k$ is the best fitness value found by the whole particles. If the next best group fitness value is not better than the previous one, then $gbest_i^{k+1}$ is equal to $gbest_i^k$. Generally, the initial velocity is randomly generated within the boundary of the search space. The updated velocity as v_i^{k+1} used to update the next iteration particle position definded as following,

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 \left(pbest_i^k - x_i^k\right) + c_2 r_2 \left(gbest_i^k - x_i^k\right) \qquad (10)$$

where ω is an inertia weight coefficient, c_1 and c_2 are cognitive coefficient and social coefficients used to accelerate the search, r_1 and r_2 are the randomly real numbers between [0,1]. In this paper, ω defined as 0.4, c_1 and c_2 are defined as 2. Then PSO would update the particle position using the updated velocity as following.

$$x_i^{k+1} = x_i^k + v_i^{k+1} \qquad (11)$$

In this study, x_i^k represents the ratio between a solar capital expenditure to the total investment constraint and v_i^{k+1} is the probability used to update the next x_i^{k+1}.

3.5. Problem formulation and calculation procedure

In this paper, the wind turbine is initially selected from 225kW to 2000kW because of its discrete capacity characteristics. The wind turbine installed area is calculated based on 2 times of rotor diameter spacing (2D). Next, the capacity of solar PV modules is randomly generated based on capital expenditure. To optimal of HRES both wind turbine and solar PV modules sizing, this paper used economical fitness function is to minimize the HRES cost of energy (COE_h) as Eq.(12)

$$\text{Minimize : fitness function} = \min\left(COE_h\right)$$
$$= \min.\left(\frac{\text{Leverlized capital expenditure} + \text{Annual expense}}{\text{HRES annaul energy production}}\right)$$
$$= \frac{\left\{\left(\frac{d(1+d)^{n_h}}{(1+d)^{n_h}-1}\right) \times CAPEX_h + \left(LLC_h + O\&M_h + LRC_h\right)\right\}}{AEP_h} \qquad (12)$$

subject to the budget investment of 3.22M$ (100 Million THB) and the lifetime of the project (n_h) is 20 years for wind energy and 25 years for solar energy following the utility contracts,

where ;

$AEP_h = P_h \times 8760$ (kWh/year) when,
P_h = average power generation of renewable source (kW),
$CAPEX_h$ = capital expenditure of renewable source,
LCC_h = land lease cost of renewable source,
$O\&M_h$ = Operation and maintenance cost,
LRC_h = Levelized replacement cost,
d = the discount rate as 10%

Note : subscript h refer to renewable energy source (h=s for solar, h= w for wind)

To evaluated the COE_h, the overall procedure to evaluate the HRES optimization is shown in Figure 8. Firstly, the HRES input parameters including budget constraint, wind distribution and solar irradiation data, wind turbine and solar PV power and cost model were defined. Wind turbine sizing from 255kW to 3000kW as in Table 1 is selected as the discrete input parameters. The wind turbine power curve in Eq (1) and the cost component from Table 1 are applied to determine the wind cost of energy (COE_w). The solar PV capacity is randomly generated to meet the project budget constraint. Solar PV power and cost model are applied to determine the solar cost of energy (COE_s). Therefore, HRES cost of energy (COE_h) as the fitness function could be derived. In the PSO optimization process, if updated particles from a previous iteration cause the capital expenditure to exceed its maximum limit, solar PV modules are randomly reduced until each budget constraint is satisfied.

4. Result

PSO converges the fitness value as the HRES cost of energy (COE_h) between wind and solar energy at the simulated data site as shown in Figures 9 and 10. The global fitness represents the optimal solution, the mean fitness shows the diversification of the search and the group fitness reveals the minimum of each iteration.

When the single turbine rating between 225 to 900 kW is selected, the PSO would search for the optimal solar PV rating with the minimized COE_h as shown in Figure 9. While the single turbine rating 1250 to 2000 kW is selected, the PSO shows the flat group fitness of each iteration indicating the minimized COE_h is equal to the wind cost of energy (COE_w) as shown in Figure 10. The small amount of solar PV installation causes a higher COE_h than a single wind turbine installation. This shows the lower weight of investment in solar PV leading to a higher COE_s than COE_w.

Table 3 shows the comparison result of minimized HRES COE_h between the different configurations of wind turbine sizing and solar PV installation capacity with the same budget constraint. COE_s, COE_w and utilized area increase with installed capacity and therefore the optimal configuration depends on the minimal COE_h achievement. The increase wind turbine investment shows a decrease in solar PV investment; however, the higher investment than 49% at 1250kW wind turbine shows the solar PV for none because the small amount solar PV capacity provides the higher COE_h than the single wind turbine installation. The increasing capital expenditure maintains the solar capacity factor (CF_s) due to facing the same solar irradiation. While the increasing wind capacity factor (CF_w) is caused by wind speed at the higher hub height of the larger wind turbine sizing.

Fig. 8 The overall procedure of HRES optimization

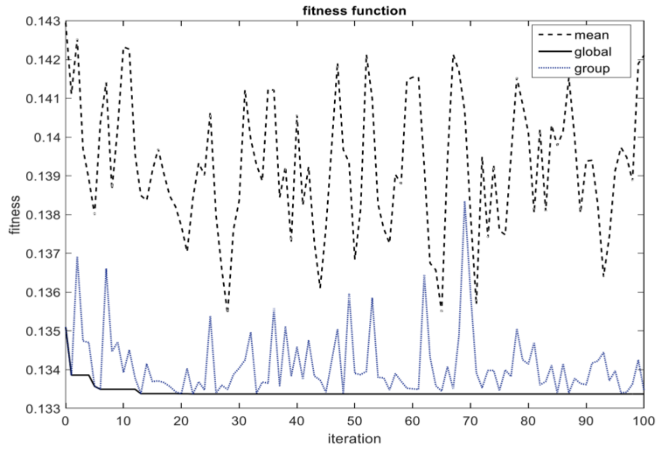

Fig. 9 The convergence of fitness function with 900 kW turbine rating and 3.22M$ of capital expenditure constrains

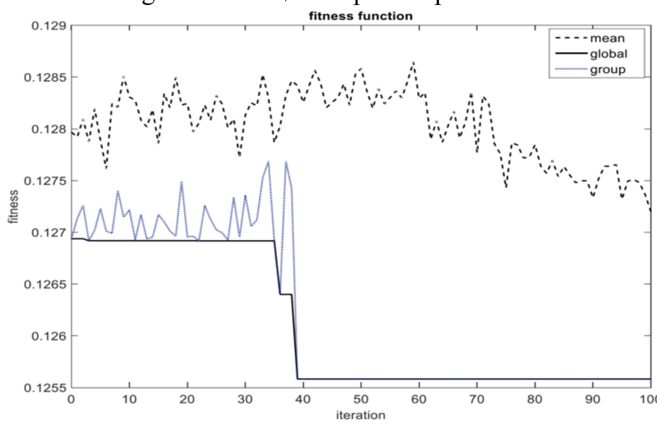

Fig. 10 The convergence of fitness function with 1,250 kW turbine rating and 3.22M$ of capital expenditure constrains

The minimum HRES COE (COE_h) of this site is 12.04 cent/kWh as equal to the COE_s at 100% solar PV investment. Due to the economy of scales model, the larger solar PV farm decreases the cost per capacity unit until its lower than the single unit of wind turbine cost with the similar installed power capacity leading to the COE_s is lower than COE_w in this simulation. As shown in Figure 11, the maximum AEP is obtained at around the budget constrain and depended on the weighting of investment. The lower investment shows the lower AEP because the algorithm achieves the lowest COE_h as the same as COE_w without solar PV installation.

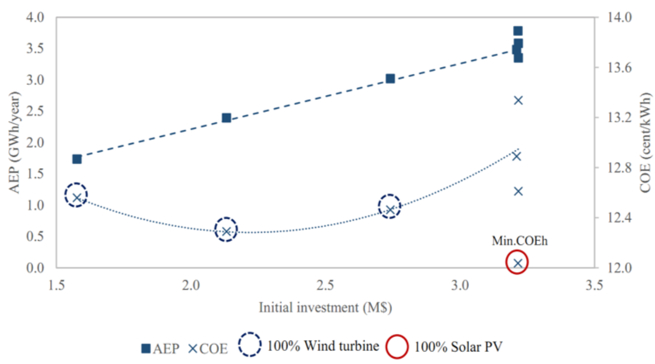

Fig. 11 AEP and COE to Capital expenditure with 3.22M$ of investment constrain

Table 3. Comparison result of HRES optimization with 3.22M$ capital expenditure constraint

wegiht of wind to total investment **wegiht of solar to total investment**		**0%** **100%**	**9%** **91%**	**24%** **76%**	**35%** **65%**	**49%** **0%**	**66%** **0%**	**85%** **0%**
List	Unit							
Budget funding	(M$)	3.22	3.22	3.22	3.22	3.22	3.22	3.22
Capital expenditure	**(M$)**	**3.22**	**3.22**	**3.21**	**3.22**	**1.58**	**2.13**	**2.74**
- Invest on wind tubine	(M$)	0	0.30	0.76	1.12	1.58	2.13	2.74
- Invest on solar PV	(M$)	3.22	2.92	2.45	2.09	0	0	0
Total capacity	**(kW)**	**2,778**	**2,714**	**2,706**	**2,617**	**1,250**	**1,650**	**2,000**
Price/total power	($/kW)	1,157	1,185	1,186	1,229	1,261	1,292	1,371
- Wind tubine rating	(kW)	0	225	660	900	1,250	1,650	2,000
- Installed Solar PV	(kW)	2,778	2,489	2,046	1,717	0	0	0
Avg. HRES power	**(kW)**	**431.6**	**409.1**	**397.4**	**382.5**	**197.9**	**273.2**	**344.6**
- Average wind power	(kW)	0	22.5	79.5	115.8	197.9	273.2	344.6
- Average solar power	(kW)	431.6	386.7	317.9	266.7	0	0	0
CF HRES (CFh)		**0.155**	**0.151**	**0.147**	**0.146**	**0.158**	**0.166**	**0.172**
- CF Wind (CFw)		0	0.100	0.120	0.129	0.158	0.166	0.172
- CF Solar (CFs)		0.155	0.155	0.155	0.155	0	0	0
COE HRES	**(c/kWh)**	**12.04**	**12.61**	**12.89**	**13.34**	**12.56**	**12.29**	**12.46**
- COE Wind energy	(c/kWh)	0	20.53	15.03	15.18	12.56	12.29	12.46
- COE Solar energy	(c/kWh)	12.04	12.15	12.35	12.54	0	0	0
Utilized area	**(10^3 m^2)**	**19.45**	**20.78**	**23.16**	**26.42**	**19.60**	**25.60**	**32.40**
- Wind turbine area	(10^3 m^2)	0	3.36	8.84	14.40	19.60	25.60	32.40
- Solar farm area	(10^3 m^2)	19.45	17.42	14.32	12.02	0	0	0
AEP	(GWh/y)	3.78	3.58	3.48	3.35	1.73	2.39	3.02
Revenue	(M$/y)	0.69	0.66	0.64	0.62	0.34	0.47	0.59
ROI		21.4%	20.4%	20.0%	19.4%	21.4%	21.9%	21.5%

The revenue increases following capital expenditure and achieve the maximum at the same of maximum AEP. As shown in Figure 12, the ROI inversely has characteristics with COE_h. The maximum ROI locates on the investment in the single 1650kW wind turbine rating with 12.29 cent/kWh COE_h which is higher than the lowest 12.04 cent/kWh COE_h of the 100% solar PV installation because the higher wind energy FIT (FIT_w=19.50 cent/kWh in Thailand [17]) than the solar energy FIT (FITs=18.21 cent/kWh in Thailand [17]). In addition, the revenue shows the same characteristic with AEP.

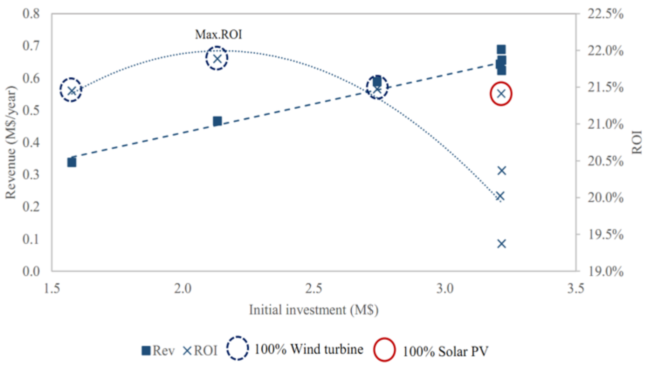

Fig.12 Revenue and ROI to Capital expenditure with 3.22M$ of investment constrain

This result presents the comparison of COE in different HRES configurations with the same site data. The other reference works could not directly compare with this result because of the diversity of location-based data. However, the Global weighted average total installed costs, capacity factors and COE as the International Renewable Energy Agency (IRENA) database [30] would be used to compare with this paper as shown in Figure 13 for solar PV and Figure 14 for onshore wind. From Table 3, COE_h ranges between 0.1204 – 0.1334 $/kWh which is higher than the average COE in the IRENA database on both wind energy cost at 0.06 $/kWh and solar energy cost at 0.10 $/kWh. The installation cost per capacity of this paper ranging between 1157-1371 $/kW is within the average range; however, the HRES capacity factors (CF_h) ranging between 14.6% - 17.2% is lower than the average CF_s and wind CF_w in the database leading to higher in COE_h as shown. Especially in wind energy shows much lower CF_w and much higher in COE_w than average in the database because the wind power from the wind speed data is in class 1 with 4.40 m/s of average wind speed at 40-meter height [31].

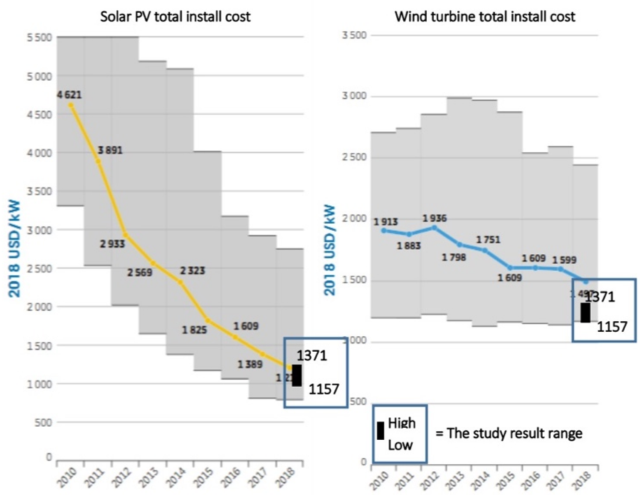

Fig. 13 Global weighted average total installed costs for solar PV and onshore wind, 2010–2018 [30] compare to the result of study.

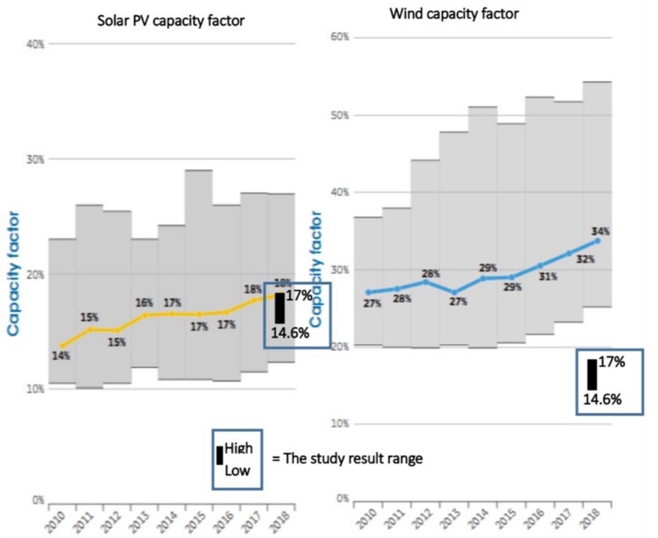

Fig. 14 Global capacity factors for solar PV and wind, 2010–2018 [30] compare to the result of study.

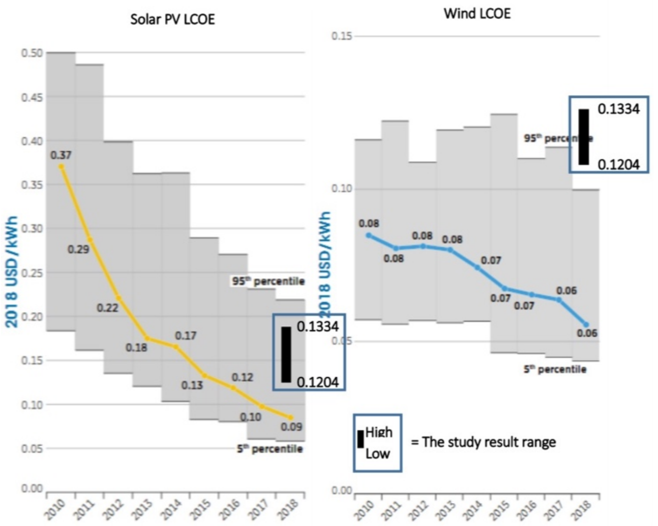

Fig. 15 Global LCOE for solar PV and onshore wind, 2010–2018 [30] compare to the result of study.

5. Conclusion

Among the renewable energy sources, wind energy and solar energy are the most utilized due to technology achievement and commercial economy of scale in production enhancing to lower cost in manufacturing. The trend to implement both renewable sources as the electric distributed generation. However, the employment of solar and wind as the individual reliable renewable source would lead to oversizing of specification design and higher COE. Therefore, HRES was developed to integrate the multiple renewable sources performing in more reliable and lower the COE_h.

This paper developed the HRES model both energy production and lifetime cost of the project. PSO was implemented to minimize COE_h of the designed configuration. The wind speed and solar irradiation data from a particular site are used to determine the energy potential following the HRES configuration. The wind power is extracted in corresponding to any range of wind speed using the wind turbine power curve. While the solar power is generated from solar PV module. The investment per capacity of the solar PV site is collected from commercial suppliers. However, the wind turbine cost are derived from the component cost model developed by NREL. Once the wind turbine and PV module are configured as HRES, the COE_h as the objective function can be determined. Then, the developed PSO is used to search for the optimal HRES configuration to minimize COE_h within the investment constraint. The minimum COE from this study at 0.1204 \$/kWh was in the 95th percentile of the global renewable power generation cost database from IRENA ranging between 0.06 – 0.22 \$/kWh for solar energy and 0.04 – 0.10 \$/kWh for wind energy but higher than the average value because of the low potential on both solar radiation and wind speed data from the particular site. However, PSO as the preliminary design method could be determined the optimal HRES with minimized COE when compare with the conventional design within the investment constraint.

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