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PoPA – SHARPS: A New Framework for Cost-Effective Design of Hybrid Power Systems

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Development of Power Pinch Analysis (PoPA) for the design and optimisation of Hybrid Power Systems (HPS) is steadily progressing. Even though PoPA has been developed for widespread applications in HPS design analysis, the economic aspect still needs more attention. This work presents a new framework for the design of a cost-effective HPS by incorporating PoPA with a cost-screening tool known as the Systematic Hierarchical Approach for Resilient Process Screening (SHARPS). SHARPS which was originally developed to screen various process changes options in water network is adapted to imbed cost analysis and renewable energy (RE) technology screening in power network. Demonstration on an illustrative case study shows that the proposed framework can provide the best HPS scheme considering the system efficiency, while satisfying the desired payback period.

1. Introduction

Power Pinch Analysis (PoPA) has been among the next-generation of the insight-based graphical and algebraic Process Integration tools. Following the development of earlier pinch analysis techniques, PoPA was initially introduced to complement the relatively established modelling tools for the optimal planning and design of Hybrid Power Systems (HPS). To date, PoPA has been developed for widespread applications including electricity targeting and allocations (Mohammad Rozali et al., 2012), optimal sizing (Mohammad Rozali et al., 2014), load shifting (Mohammad Rozali et al., 2015b), storage design (Mohammad Rozali et al., 2015c), and diesel plant expansion (Mohammad Rozali et al., 2015a). Though PoPA could lead to optimal renewable energy (RE) utilisation and electricity cost reduction, some RE generation technologies in HPS may be costly and thus affect the economics.

Numerous researches on the design of HPS considering the economic analysis have been conducted. Ramli et al. (2016) determined the best size for wind-solar hybrid system components based on the minimum cost of energy production. The economic model was developed in HOMER software, using the net present cost (NPC) and levelised cost of energy (COE). Stadler et al. (2016) formulated an optimal HPS design using a mixed integer linear programming (MILP) to achieve the maximum cost benefits in the view of both the consumer and the distribution network operator. The operating expenses have been successfully minimised while maximising the self-sufficiency of the system. The economic feasibility of integrating hybrid solar thermal-PV with micro-cogeneration system in a building was scrutinised by Romero Rodríguez et al. (2016) using TRNSYS software. Life Cycle Cost Analysis for different system configurations was performed in order to establish the most optimal solution with minimum energy consumption and emissions. Sensitivity analysis of costs has also been done by the authors to address the continuous changing of renewable technologies costs.

The aforementioned works mostly focus on the finding of minimum system and energy costs, given a specific technology of the RE. It has never been considered to screen various applicable RE generation technologies at the early design stage, in order to maximise the potential savings and minimise the investment, ahead of design. There is a clear need to screen all the RE technologies involve, as different technologies may have different costs and efficiencies, and thus affect the overall system economics.

Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) is known as a cost-screening tool that can lead to a cost-effective network design with the minimum resource utilisation within the desired payback period (Wan Alwi and Manan, 2006). It was initially developed to economically screen various process changes options, specifically for water network. Minimum water targets was firstly targeted using the water cascade analysis (WCA) method, before the cost-effective minimum water network was established with SHARPS strategy. It was later extended by Lawal et al. (2012) to determine a cost-effective carbon emission reduction in buildings. Analogous to the water network, the SHARPS was used to screen carbon reduction potentials in buildings based on the Carbon Emission Pinch Analysis (CEPA) approach.

Application of SHARPS for the cost-screening in power network has never been presented. In this paper, PoPA and SHARPS techniques are incorporated to establish a cost-effective HPS that achieves the minimum electricity targets within a desired payback period. The proposed framework provides a quick means to guide and screen RE generation technologies involve in the HPS, with respect to the investment and electricity cost savings.

2. Methodology

This section describes the step-wise procedure of a new framework to obtain a cost effective HPS that achieves the minimum electricity targets, within a desired payback period. The new framework is implemented as follows;

2.1 Step 1: Set the desired payback period (PP_{set})

The desired payback period is set by the designers or plant owners. It can vary depending on the type of system. In this study, the payback period for a HPS with wind and solar energy was set to 9 y.

2.2 Step 2: Determine the minimum electricity targets using PoPA

A PoPA technique named Modified Storage Cascade Table (SCT) was used to establish the optimal size for RE generators and the amount of outsourced electricity required. A HPS with solar PV and wind turbine technologies was studied in the illustrative case study. Figure 1 shows the solar insolation and wind speed for the site of where the HPS is located, while Table 1 tabulates the average daily load profile of the system.

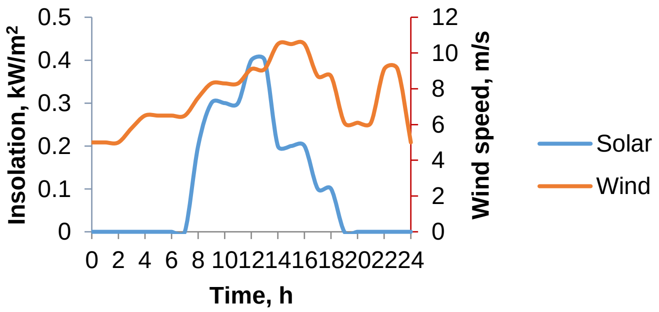

Figure 1: Average hourly insolation and wind profile for illustrative case study

Table 1: Power demands for illustrative case study

Power demand appliances		Time, h		Time interval, h	Power rating, kW	Electricity consumption, kWh
AC	DC	From	To			
	Appliance 1	0	24	24	30	720
Appliance 2		8	17	9	50	500
	Appliance 3	0	24	24	20	480
Appliance 4		8	17	9	50	500
Appliance 5		8	22	14	40	480

Initially, the HPS applied the PV and wind turbine facilities as specified in Table 2.

Table 2: Parameters of RE technologies (U.S. Energy Information Administration, 2013)

Solar PV panel	Efficiency	0.164
	Capital cost, USD/kW	4,183
	Operating and maintenance cost, USD/kW.y	27.75
	Total area, m^2	800
Wind turbine	Efficiency	0.85
	Capital cost, USD/kW	2,213
	Operating and maintenance cost, USD/kW.y	28.07
	Swept area, m^2	200
	Air density, kg/m^3	1.225

Based on Figure 1, the hourly generation profile from the solar (P_{PV}) and wind (P_{wind}) sources was calculated using Eq(1) and Eq(2) (Mohammad Rozali et al., 2014).

$$P_{PV}(t) = I(t)A\eta_{PV} \tag{1}$$

$$P_{Wind}(t) = ½\rho Av(t)^3 C_p \tag{2}$$

Where
$I(t)$ = insolation data at time t (kW/m^2); A = area of PV panels/swept area of the rotor (m^2); η_{PV} = overall efficiency of PV panels and DC/DC converter; ρ = the air density (kg/m^3); $v(t)$ = wind speed at time t (m/s); C_p = efficiency of the wind turbine.
Given the data on the generation and load profiles, the modified SCT can be constructed using the procedure as described by (Mohammad Rozali et al., 2013).

2.3 Step 3: Generate the investment vs. annual savings (IAS) composite plot

IAS composite is a plot that offer the insights on the economics of each RE technology involve in the studied system. It should covers all the power generation technologies, which are in this case solar PV and wind turbine. The investment is the capital cost of the technology. The annual savings can be obtained with Eq(3), which is the difference of the reduced outsourced electricity cost with the cost of electricity production by the RE technology.

$$\text{Net annual savings} = (O \times D \times T_E) - (MOES \times D \times T_E) - (S \times OM) \tag{3}$$

Where
O = amount of daily electricity outsourced without generation from RE (kWh); D = total days for a year operation = 365 d; T_E = tariff rate for electricity = 0.09 USD/kW (Tenaga Nasional Berhad, 2016); $MOES$ = amount of minimum outsourced electricity targeted with modified SCT; S = RE generator capacity; OM = annualised operating and maintenance cost of RE technology.

2.4 Step 4: Compare the *TPP* with the PP_{set}

The *TPP* should match the desired payback period, PP_{set}. If $TPP \le PP_{set}$, the designers can proceed with the current HPS design. On the other hand, if $TPP > PP_{set}$, measures should be taken to tailor the HPS in order to satisfy the desirable investment limits. In this case, the designers can consider replacing the RE technology that resulted in the steepest slope, with the one that could give less steep gradient. This strategy is called the substitution.

3. Results and discussion

Tables 3a and 3b show the completed modified SCT for the illustrative case study. The key electricity targets that should be extracted from the modified SCT are the amount of annual outsourced electricity and the RE generator size. This is because the amount of annual outsourced electricity influences the annual savings, while the size of the generator affects the investment.
The amount of electricity that should be outsourced for AC and DC demands respectively can be observed from Column 12 (for the first day operation) and Column 14 (for the continuous 24-h operation) of the table. It was assumed that the AC and DC outsourced electricity influence the net savings of wind turbine technology and solar PV facility respectively.

Table 3a: Modified Storage Cascade Table for illustrative case study

1	2	3		4		5		6		7	
Time, h	Time interval duration, h	∑Power source rating, kW		∑Power demand rating, kW		∑Electricity source kWh		∑Electricity demand, kWh		Electricity surplus/deficit, kWh	
		AC	DC	AC	DC	AC	DC	AC	DC	AC	DC
0											
	3	12.25	0	0	50	36.75	0	0	150.00	36.75	-150.00
3											
	1	19.12	0	0	50	19.12	0	0	50.00	19.12	-50.00
4											
	4	26.91	0	0	50	107.64	0	0	200.00	107.64	-200.00
8											
	1	41.34	26.24	140.00	50	41.34	26.24	140.00	50.00	-98.66	-23.76
9											
	3	56.04	39.36	140.00	50	168.12	118.08	420.00	150.00	-251.88	-31.92
12											
	2	73.85	52.48	140.00	50	147.70	104.96	280.00	100.00	-132.30	4.96
14											
	3	113.45	26.24	140.00	50	340.35	78.72	420.00	150.00	-79.65	-71.28
17											
	2	64.53	13.12	40.00	50	129.06	26.24	80.00	100.00	49.06	-73.76
19											
	3	22.24	0	40.00	50	66.72	0	120.00	150.00	-53.28	-150.00
22											
	2	73.85	0	0	50	147.70	0	0	100.00	147.70	-100.00
24											

Table 3b: Modified Storage Cascade Table for illustrative case study (continued)

8		9	10	11	12		13	14	
Converted surplus, kWh		Charging/ Discharging quantity (AC), kWh	Discharge for DC deficit, kWh	Start up			Operation		
				Storage capacity, kWh	Outsourced electricity, kWh		Storage capacity, kWh	Outsourced electricity, kWh	
AC	DC				AC	DC		AC	DC
				0	0		36.28		
34.91	0	0	0	0	0	115.09	0	0	82.43
18.16	0	0	0	0	0	31.84	0	0	31.84
102.26	0	0	0	0	0	97.74	0	0	97.74
0	0	0	0	0	98.66	23.76	0	98.66	23.76
0	0	0	0	0	251.88	31.92	0	251.88	31.92
0	4.71	0	0	0	127.59	0	0	127.59	0
0	0	0	0	0	79.65	71.28	0	79.65	71.28
46.61	0	0	0	0	0	27.15	0	0	27.15
0	0	0	0	0	53.28	150	0	53.28	150
140.32	0	40.32	0	36.28	0	0	36.28	0	0

Figure 2 shows the IAS plot for the illustrative case study. The payback period for each RE technology, i.e. solar PV and wind turbine can be translated from the gradient of the curves. Steeper gradient indicates the technology with higher investment per unit savings, or the more costly scheme over the other. It can be observed from the figure that solar PV slope (m_1) is slightly steeper compared to the wind turbine (m_2).

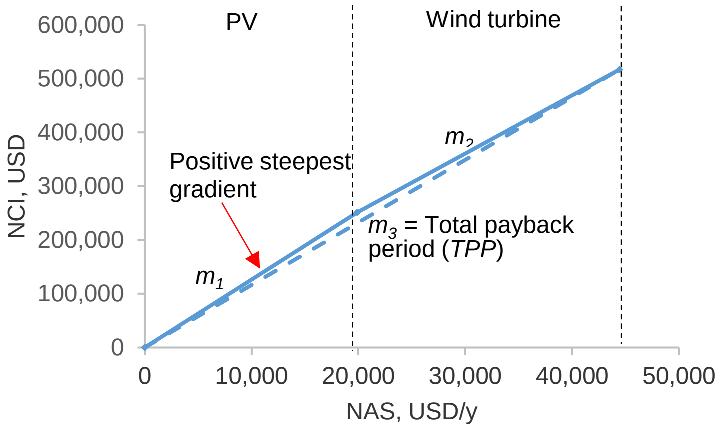

Figure 2: Investment vs. annual savings (IAS) plot

In the same plot, preliminary cost estimate of the total payback period (*TPP*) can be obtained by drawing a straight line connecting the starting and the end points of the IAS plot (see Figure 2). The slope of this line (m_3) gives the total payback period of the HPS, before SHARPS substitution strategy implementation. For the illustrative case study, the *TPP* obtained from the IAS plot is 11.6 y. Since the *TPP* is higher than the PP_{set} (9 y), various types of solar PV technology were screened to implement the substitution strategy. Table 4 lists a number of solar PV technologies available in the market (International Renewable Energy Agency, 2012).

Table 4: Comparison of PV technologies (International Renewable Energy Agency, 2012)

	Efficiency	Capital cost, USD/kW	Operating and maintenance cost, USD/kW.y
Single crystalline silicon (sc-Si)	0.15	1,400	6.5
Cadmium Telluride solar cells (CdTe)	0.08	900	6.5
Amorphous silicon (a-Si)	0.05	800	6.5

It can be seen from Table 4 that different PV technologies have different costs and efficiency. Inexpensive technology is very attractive, but it may require higher amount of outsourced electricity, thus higher annual electricity cost due to its poor performance. Therefore, to reduce the steepest gradient according to the substitution strategy, the technology with highest efficiency, but with lesser total investment, i.e. sc-Si was selected to replace the initial PV facility. Figure 3 shows the IAS plot with the revised *TPP* after the substitution strategy.

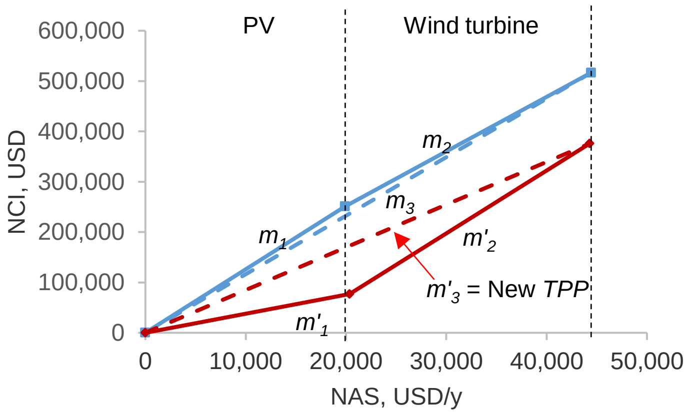

Figure 3: IAS plot after substitution strategy

As observed, substituting the initial PV scheme with sc-Si gives a less steep slope (m'_1), and accordingly yields a smaller *TPP* value (m'_3). After SHARPS screening and substitution strategy, the HPS achieved the payback period of 8.5 y. Since this value satisfies the desired payback period of 9 y, the HPS design is cost-effective and can be proceeded.

4. Conclusions

A new framework for the design of cost-effective HPS has been proposed. The framework incorporated the PoPA and SHARPS approaches, to guide the screening of various RE technologies during the early design stage. It addresses the issue related to the trade-off between the efficiency and the costs of RE technologies. Results from the illustrative case study shows that the proposed framework allows HPS design with minimum electricity targets to be achieved, within the desired payback period of 8.5 y. Further studies should include the possibility of implementing intensification strategy apart from the discussed substitution strategy.

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