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Multi-objective optimal sizing of a hybrid concentrated solar power-biogas for desalination and power generation

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ABSTRACT

The use of a fully renewable energy system (RES) to power mid- and low-scale off-grid systems is an attractive alternative solution to replace fossil fuel technologies in order to meet the ever-growing demand and tackle environmental problems. In this study, the design optimization of a hybrid solar biogas, Organic Rankine Cycle (ORC-Toluene) and Air Gap Membrane Distillation (AGMD) for desalination and electric power generation is presented. Three objective functions namely, maximizing power and water production, and minimizing the unit exergy product costs has been formulated. The turbine efficiency, top ORC vapor temperature and ORC condenser temperature has been selected as the decision variables. The non-dominated sorting genetic algorithm (NSGA-II) has been employed to solve the optimization problem and produce a Pareto frontier of the optimal solutions. Further, the TOPSIS approach has been used to select the optimal solution from the Pareto set. The study constitutes the first attempt to holistically optimize such a hybrid off-grid cogeneration system in a robust manner. It is found that the proposed system is capable of generating 1960 kW of electricity and 8 kg/m^2h freshwater with 11 $/GJ unit exergy product costs.

Keywords: Hybrid solar biogas, Organic Rankine Cycle, Air gab membrane distillation, multi-objective optimization, TOPSIS.

1. INTRODUCTION

The intensive use of the fossil fuels to meet the world energy and water demand has caused several environmental issues, such as global warming, air pollution and ozone depletion. Therefore, the use of a fully renewable energy system to operate water and power plants have become one of the most important research areas in energy systems. The free and abundant solar energy source makes concentrated solar power (CSP) an attractive option to solve the energy crisis in the future. The intermittency is the biggest drawback of solar CSP power plants. This problem can be compensated by utilizing thermal energy storage (TES). However, the additional TES greatly increases the solar thermal power system costs. Therefore, to solve such expensive costs and technical difficulties, hybridizing solar thermal power with biogas energy is a promising and attractive option. The hybridization of solar CSP and biogas from waste will not only reduce the investment and Levelized Cost of Energy but enhance the power dispatchability and system reliability [1]. Such systems have some advantages, such as (i) utilizing the human, animal, and agriculture wastes, (ii) reducing the greenhouse gas emissions and (iii) overcoming the uncertainty of the solar thermal systems.

To implement and fully utilize the hybrid solar biogas system a combination of multi-objective optimization and multi-criteria decision making (MCDM) tools have been employed. The optimization of the fully renewable decentralized systems is crucial as this will result in more efficient designs and will eventually assist to phase out existing fossil fuel technologies.

Several studies have been conducted to optimize the design of hybrid CSP plants using the single and multi-objective optimization approach [2-7]. However, none of these studies consider the integration of the CSP-biogas to power ORC and AGMD for desalination and power generation. Typically, solar PTC linked with wind/thermal energy storage for combined heat and power is the most popular integration approach that has been investigated in the literature [8-11].

As it can be observed from the literature review and to the best of the author’s knowledge, multi-objective optimization has not been performed for decentralized hybrid CSP-biogas to drive ORC and AGMD for power-water productions, and this forms the basis for this study. First, a three objective optimization is preformed using a non-dominated sorting genetic algorithm which present the results in terms of a Pareto set. Subsequently, a MCDM tool is deployed to select the optimal design parameter from the Pareto set. This robust optimization can pave the way for further research on scale up cases.

2. SYSTEM DESCRIPTION

The system comprises a parabolic trough collector, anaerobic biogas digestion and organic Rankine cycle coupled with an air gap membrane distillation for cogeneration application. The parabolic trough collector is considered the prime mover and the biogas is utilized as a backup energy source during the periods of no or limited sunlight to achieve higher stability and reliability. A schematic diagram of the proposed hybrid solar biogas to power ORC and AGMD system for cogeneration application is illustrated in Figure 1.

maximize the net output work (W_{net}) (Eq. (1, 2 and 3)), maximize the total amount of distilled water (Eq. (4)) and minimize the unit exergy product costs (Eq. (5)). The design variables and their range of variations that have been considered for the multi-objective optimization of the hybrid system are given in Table 1. The non-dominated sorting genetic algorithm (NSGA-II) [12] is used as the multi-objective optimization method for optimizing the objective functions.

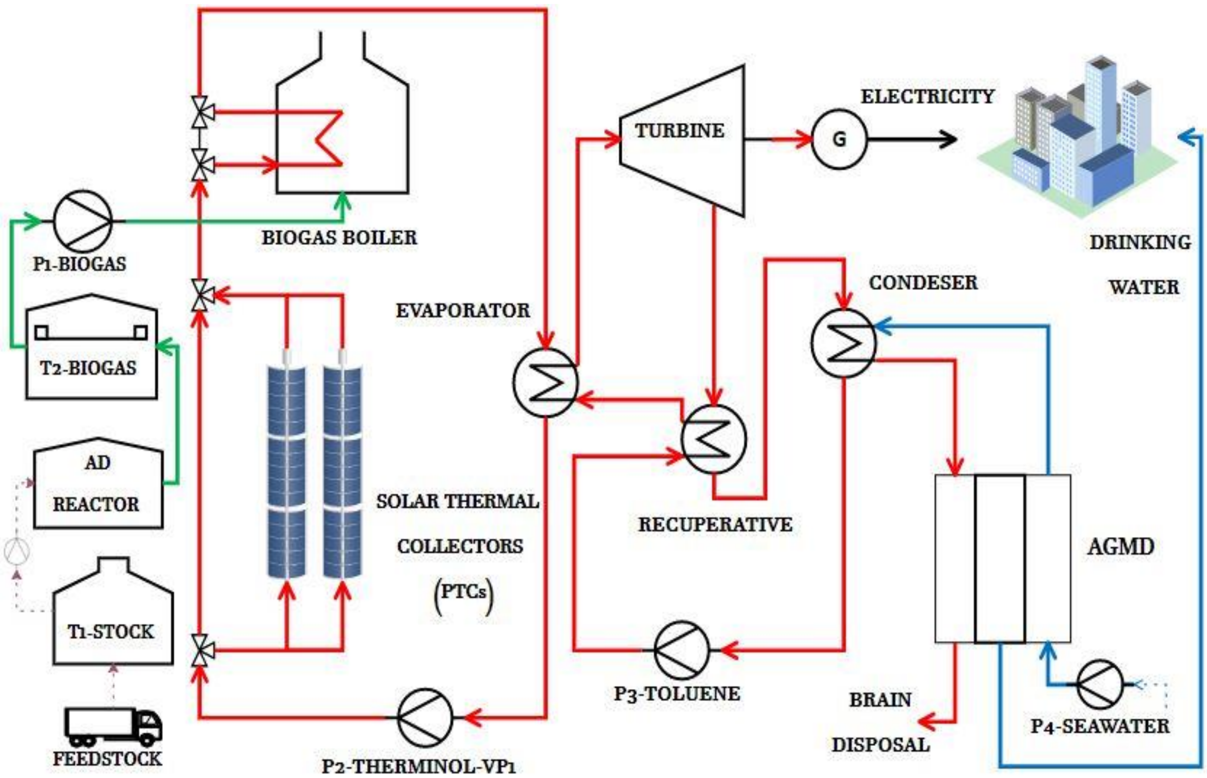

Figure 1. A schematic diagram of the proposed system.

3. MULTI-OBJECTIVE OPTIMISATION AND DECISION-MAKING PROCEDURE

The obtained procedure of multi-objective optimization and the decision-making tool is described in this section.

3.1 Multi-objective optimization

The key aim of the multi-objective optimization of the integrated PTC-AD-ORC-AGMD systems is to achieve maximum power and water production with minimum possible cost. The three selected objective functions are: The net output work of the ORC system in kW is defined as follows:

$$W_{net} = (W_{turbine} - W_{pump}) \quad (1)$$

$$W_{pump} = \frac{\dot{m}\Delta p}{\rho \mu_p} \quad (2)$$

$$W_{turbine} = \dot{m}(h_i - h_{os})\mu_t \times \mu_g \quad (3)$$

The total amount of distilled water in kg/m^2h is calculated by:

$$J_p = C_w \delta (T_{hi} - T_{ci}) \quad (4)$$

where T_{hi} and T_{ci} are the temperature at the feed side of the membrane, °C, and at the cold side of the condensation section, and δ is the relative viscosity.

The unit exergy product costs (C_p) in $/GJ are calculated based on the overall thermo-economic equation:

$$C_p = 1000000\Big(\big((\text{Cooling feed cost } (\tfrac{\$}{\text{kJ}}) \times \text{Feed exergy (kW)}\big) + \big(\text{Cost of power } (\tfrac{\$}{\text{kJ}}) \times \text{Power output(kW)}\big) + (\tfrac{\text{IC\&OM Costs}}{3600} (\tfrac{\$}{\text{h}}))\Big) / \text{Distilled exergy from AGMD (kW)}\Big) \quad (5)$$

Table 1. Considered design variables and range of variations for the optimization.

Decision variables	Range of variation
$\mu_{turbine}$	[0.7, 0.95]
T_{vo}, °C	[200, 300]
T_{cond}, °C	[30, 70]

The NSGA-II optimization algorithm has been implemented in MATLAB. A population size of 50, generations of 100 cross over function of 0.8 and Pareto fraction of 0.5.

3.2 Decision making procedure

The decision making method is used in selecting the optimal solution from the Pareto fronts. The Pareto front in multi objective optimization contains a set of optimal solutions which means there is not a single optimal solution. Therefore, to select the optimal solution, a technique for order preferences by similarity to the ideal solution (TOPSIS) is used in this study.

The following steps are the implementation process of the TOPSIS:

i. Calculate the weighted normalized optimized results. The weighted normalized data uij is given as:

$$u_{ij} = w_j \times \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \quad i = 1,2..n; \quad j = 1,2..m \quad (6)$$

where w_j is the weight obtained from the criteria of the decision matrix and x_{ij} are the optimized results.

ii. Compute the separation of each of the weighted normalized results from the negative and positive ideal solutions, NIS and PIS, respectively. The Euclidean distance between an alternative and the PIS, NIS are calculated using equation (7) and (8), respectively:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(u_{ij} - u_j^+\right)^2} \quad i = 1,2 \ldots n \quad (7)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(u_{ij} - u_j^-\right)^2} \quad i = 1,2 \ldots n \quad (8)$$

where the positive ideal solution is $u_j^+ = \max_{\forall i} u_{ij}$ and negative ideal solution is $u_j^- = \max_{\forall i} u_{ij}$.

iii. Compute and order the ranking index in a descending order. The ranking index is calculated using:

$$RI_i = \frac{\boldsymbol{D_i^-}}{\boldsymbol{D_i^-} + \boldsymbol{D_i^+}} \quad i = 1,2\ldots n \quad (9)$$

Based on this approach, the alternative with the highest RI_i is selected.

The decision matrix and the criteria used to calculate the weight for each of the alternatives in this study is shown in Tables 2 and 3, respectively.

Table 2. Decision matrix for the TOPSIS analysis.

	Power	Water	Costs
Power	1	1/4	1/3
Water	4	1	3
Costs	3	1/3	1

Table 3. Judgement criteria for the decision matrix [13].

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values

4. RESULTS AND DISCUSSION

The proposed system has been designed through advanced modeling in the MATLAB/ Simulink® and validated against experimental data in our pervious study [1], and very good agreements between the predicted results and experimental data have been reported. In this study, the developed model in the previous study [1], have been used to obtain the objective functions and to implement the multi-objective optimization. In this section, the Pareto optimal frontier obtained from this multi-objective optimization problem is presented.

Figure. 2 shows the Pareto frontier of the multi-objective optimization and this is presented in three-dimensional space. The conflict in the objectives function is evidenced by the spread in the optimized data.

As seen in Figure. 2, the optimal data present both dominated and non-dominated solutions. It is also evident that there is no single solution that maximizes all the objectives; hence, in order to select an optimal solution TOPSIS MCDM tool need to be applied.

The optimum solution for the decision-making tool is obtained and indicated in Figure 2, and the corresponding decision variables for the selected solution are presented in Tables 4.

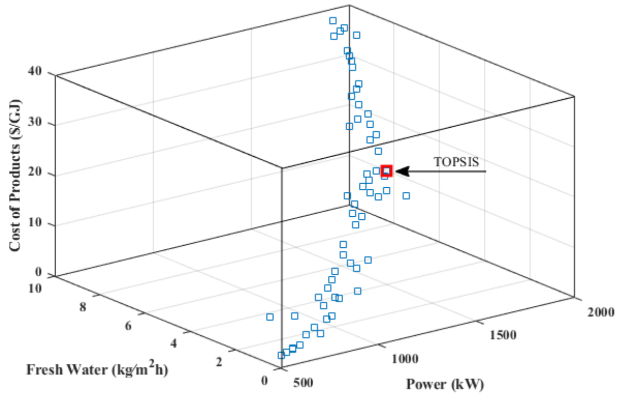

Figure 2. Pareto front for multi-objective optimization result.

Table 4. Values of decision variables for the hybrid concentrated solar power-biogas system.

Decision variables	TOPSIS
$\mu_{turbine}$	0.83
T_{vo}, °C	283
T_{cond}, °C	37

Figure 2. shows that the Hybrid PTC-AD-ORC-AGMD system is capable of delivering 1960 kW of electricity and 8 kg/m^2h of distilled fresh water at unit exergy product costs of 11 $/GJ. The values were observed for the decision variables; turbine efficiency = 0.83 (-), top ORC vapor temperature = 283 (°C) and ORC condenser temperature = 37 (°C), as indicated in Table 4. Thus, the calculation procedures showed that using NSGA-II multi-objective optimization algorithm and multi-criteria decision-making techniques (TOPSIS) in a simultaneous process can lead to the achievement of the best performance configuration for the proposed hybrid cogeneration system that produces higher amounts of power and fresh water and has a lower cost of the products. It should be noted that the current optimum value relies on the TOPSIS ranking as decided by the authors and different results will be obtained for different rankings. Hence, the main objective of the hybridizing multi-objective optimization with MCDM is to showcase a method that can lead to a single optimum based on the practitioner's preferences.

5. CONCLUSION

In this study, a combination of NSGA-II multi-objective optimization and multi-criteria decision-making techniques (TOPSIS) were deployed to solve optimization problem and select the best configuration.

The multi-optimization is performed in order to find optimum design points where the system performance is maximized, and the unit exergy product costs is minimized.

The optimal obtained result showed that the integrated PTC-AD-ORC-AGMD system is capable of generating 1960 kW of power (electricity) and 8 kg/m^2h of distillated water at unit exergy product costs of 11 $/GJ. This amount of produced electricity-water can fulfill the electrical and water demands of small-scale communities, facilities, nomads' spots, tourist villages, rural areas and, etc.

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