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Optimisation of a Grid-Connected Hybrid Renewable System at Peak Load

Bader Alqahtani, Manosh C Paul*, Jin Yang, Xiaolei Liu

Systems, Power & Energy Research Division, James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

*Corresponding author: Manosh.Paul@glasgow.ac.uk

ABSTRACT

In this study, a hybrid renewable energy system consisting of photovoltaics (PVs), wind turbines, bioenergy, and pumped hydropower energy storage (PHES) is proposed. This study aims to optimise the size of the hybrid system components based on peak periods to increase the reliability of the overall system performance. The non-dominated sorting genetic algorithm (NSGA2) optimization model is developed to minimise two main objectives: loss of power supply (LPSP) and loss of renewable energy (LORE). The input variables are the number of wind turbines, the number of solar modules, the number of pumps/generators, and the capacity of the upper reservoir of PHES. The novelty of this study is to develop a multi objectives optimisation model focusing on peak load period for long time assessment taking advantage of hybridisation dispatchable and non-dispatchable renewable sources to size renewable energy components accurately. The results reveal that increasing the number of PV modules and wind turbines improves the LORE while reducing the LPSP, as it covers more demand at a given period. The best solutions obtained for the LPSP and LORE are 5% and 5%, respectively. The entire system dispatchability might be improved by increasing bioenergy power plant and PHES capacity.

Keywords: renewable/green energy resources, pumped hydropower energy storage (PHES), PV system

NOMENCLATURE

LPSP	Loss of power supply
LORE	Loss of renewable energy
HRES	Hybrid renewable energy system
PHES	pumped hydropower energy storage
NSGA2	Non dominated sorting genetic algorithm
RES	Renewable energy sources
Pymoo	Multi objective optimization in python
HRES	Hybrid renewable energy system
MSW	Municipal solid waste

1. INTRODUCTION

Renewable energy sources (RES) have been playing an essential role in lowering the usage of fossil fuels and greenhouse gas emissions [1]. They are accessible in most countries around the world, with varying levels of natural sources. This includes wind speed and solar radiation. However, most RES is intermittent due to the unpredictable nature of natural sources, leading to the importance of energy storage. Energy storage entails the storage of excess energy; this energy is then utilised when it is needed. The hybridisation of various RES connected to one or multiple energy storage technologies increases the reliability of such an energy system, whether connected to the national grid or a standalone system. Subsequently, one of the mature and large-scale storage technologies is the PHES utilised for decades. The hybrid renewable energy system (HRES) proposed in this study includes photovoltaic solar energy systems (PV), wind turbines, and a bioenergy power plant connecting to the PHES and national grid. Sizing such a system necessitates a comprehensive techno-economic assessment as well as environmental influences in order to avoid oversizing components and further energy loss. Many studies on optimisation have been conducted, particularly those considering technical and economic indicators (e.g. Levelized cost of energy)[2],[3],[4]. Regarding on-grid systems, it is worth mentioning that most studies have focused on fundamental demand characteristics in optimisation, including base and peak loads. However, a reliable source such as a gas turbine based on a reliable source (e.g. natural gas) is required to meet the peak demand. A RES without storage is unable to cover this period. The novelty of this study lies in optimising the RES based on peak load. The aim of this optimisation is to take advantage of dispatchable RES (e.g. bioenergy and largescale PHES) by increasing the reliability of the entire system at peak time.

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2. STUDY DESCRIPTION

Hourly electricity demand for the specific area in this study (Bisha) where the dam is located is shown in Figure. 1. The entire load is divided into three parts: the maximum level, average level, and minimum level. The baseload (minimum level) is intended to be covered by the national grid. The demand above the minimum (average and maximum) is considered to be the peak load, which is supposed to be covered by HRES. The meteorological data has been derived from the National Solar Radiation Database (NSRDB), which includes wind speed, solar radiation, and temperature, as shown in Figure.2. The PHES has two essential requirements: sufficient water and an appropriate elevation based on plant capacity. The south region of Saudi Arabia possesses the perfect potential to install a system like the closed-loop of PHES, and this is due to its artificial dam (King Fahad dam) and the surrounding high mountains. This region differs from others due to its potentially remarkable amount of annual precipitation. The dam has the largest storage capacity in Saudi Arabia, with an elevation up to 103 meters.

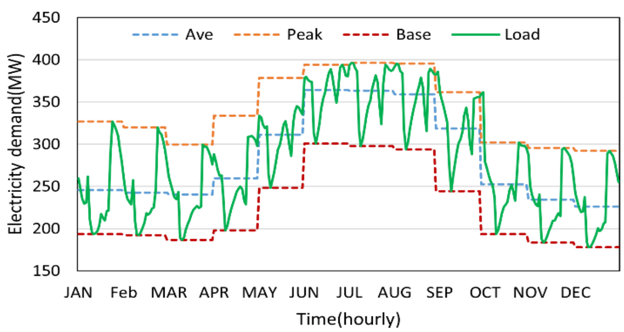

Fig.1. Electricity demand for the adopted location (South region of Saudi Arabia).

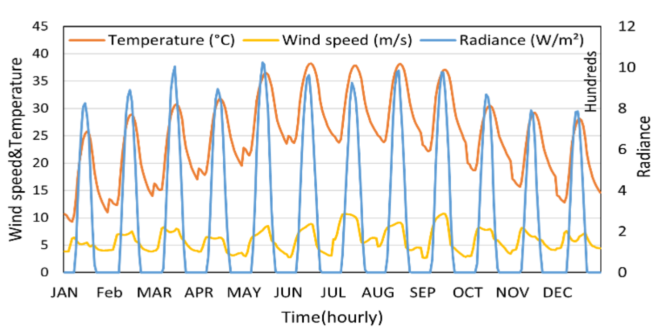

Fig.2. Hourly meteorological data of the specific location for full year.

3. MATERIAL AND METHODS

3.1 Solar energy

A photovoltaic system is defined as the exploitation of solar radiation by converting it to electricity. The KC200GT module was selected for use in this study. The amount of electricity at a specific time could be calculated as follows[5]:

$$P_{pv} = (I \times V) \times PR \times N_{pv} \quad (1)$$

$$I = I_{pv} - I_0 \left[Exp\left(\frac{V + R_s I}{V_t \times a}\right) - 1 \right] - \frac{V + R_s}{R_p} \quad (2)$$

$$I_{pv} = \left(I_{pv,n} + K_I \Delta T\right) \times \left(\frac{G}{G_n}\right) \quad (3)$$

$$I_0 = (I_{sc,n} + K_I \Delta T)/[Exp\left(\frac{\left(V_{oc,n} + K_v \Delta T\right)}{aV_t}\right) - 1] \quad (4)$$

$$V_t = \frac{N_s \times K \times T}{q} \quad (5)$$

Where P_{pv} is the power production; PR is the entire system performance ratio; I is the generated current; V is the output voltage; N_{pv} is number of PV modules; R_s is the series resistance; R_p is the parallel resistance; K is Boltzmann constant; q is electron charge; ΔT is the variation among actual and cell temperature; G is the actual irradiation.

3.2 Wind energy

The concept of wind energy is to convert the kinetic energy from wind to electricity using a wind turbine; a wind turbine is a proper mechanism for transferring mechanical energy to electricity through a generator. Based on prior evaluation of wind speed and wind farm area of an adopted location, the selected wind turbine was the Gamesa G114-2MW. The wind energy estimation is performed as follows[6]:

$$P_{wind}(v) = \frac{1}{2} \rho \times A_{bl} \times C_p \times v^3 \times \eta \times N_{wind} \quad (6)$$

$$v = v_1 * (Elv/Elv1)^{\alpha} \quad (7)$$

Where P_{wind} is power production from wind turbine; ρ; is the air density; A_{bl} is the swept area ; C_p is power coefficient ; η is the generator and rotor efficiency; N_{wind} is number of wind turbines ; Elv is the hub heght; $Elv1$ is the height of wind speed measurement tool; v_1 is the wind speed at 10 m; v is the wind speed at hub.

3.3 Bioenergy

Bioenergy is defined as taking advantage of waste material or residential organic waste to produce heat or electricity. The attractive aspect of this technology is its dispatchability of electricity, which increases the system reliability during the peak period. Furthermore, the adopted location has a magnificent opportunity to exploit the massive municipal waste and generate electricity. In this study, municipal solid waste (MSW) is an adopted ingredient used in the combustion process to create electricity (waste to energy). The estimated energy of the MSW is expressed as follows[7]:

$$E_{Bio} = LHV \times Eff_g \times Eff_p \times V_{MSw} \times \frac{1}{3600} \quad (8)$$

Where E_{Bio} is energy generated by bio power plant; LHV is the low heating value; Eff_g is the generator efficiency; Eff_p is transmission efficiency; V_{MSw} is the weight of waste material.

3.4 Pumped hydropower energy

The PHES consists of the pumps/turbines, penstocks and an upper and lower reservoir. The adopted location has high mountains of up to 400 m surrounding the artificial dam. The upper reservoir holds the water in the potential energy phase, and it is then released to the lower reservoir, passing the turbine and generating the necessary power. This technology has been widely used to cover peak time. Recently, it has gained increasing attention due to its ability to connect to intermittent renewable sources. The charging and discharging of the PHES is expressed below[8]:

$$Q_{pu} = \frac{P_{pu}\eta_{pu}}{\rho g H_{pu}} \quad (9)$$

$$H_{pu} = H_{st} + H_{loss} \quad (10)$$

$$P_{tu} = Q_{tu} H_{tu} \rho g \eta_{tU} \quad (11)$$

$$Q_{tu} = \frac{PR_v}{100} a\sqrt{2g(H_{st} * H_{loss})} \quad (12)$$

$$a = 0.25\pi D_{tu}^2 \quad (13)$$

Where Q_{pu} is the flow rate in pumping mode; P_{pu} is the excess renewable energy; η_{pu} is the pump efficiency; g is the gravity acceleration; ρ is the water density; H_{pu} is the total head; H_{st} is the static head; H_{loss} is hydraulic loss ; P_{tu} is power generated by Francis turbine; η_{tU} is the turbine efficiency ; H_{tu} is the total head in generating mode; Q_{tu} is the total flow rate in generating mode; D_{tu} is the pipe diameter; PR_v is the percentage of flow rate amount.

3.5 Optimisation procedure

The study focuses on the peak period by optimising the entire system components to raise the system's reliability. Two technical assessment indicators have been selected in this study: the *LPSP* and the *LORE*, as expressed in the equations below:

$$LORE\ (\%) = \sum_{t=1}^{T} \frac{E_{surplus}\,(t)}{Re(t)} \quad (14)$$

$$LPSP(\%) = \sum_{t=1}^{T} \frac{E_{shortage}(t)}{D(t)} \quad (15)$$

Where $E_{surplus}$ is surplus energy; Re is the available renewable energy; $E_{shortage}$ is the shortage of energy; D is electricity demand. Since the economic aspect is not involved in this study, the LORE takes priority over the LPSP to avoid oversizing the RES components. The study proposes LPSP and LORE as the two main objectives that are assumed to be minimised. Subsequently, the (NSGA2) optimisation model is developed, taking advantage of the pymoo package (multiobjective optimisation in Python) that is implemented using the Python software language[9],[10]. The optimisation model includes decision variables (number of wind turbines, the number of solar modules, the number of pump/generators, and the capacity of the upper reservoir of the PHES and lower and upper variable constraints. Each subcomponent is mathematically modelled, as explained in Section.3. The initial variables (e.g., population size, meteorological data, and hourly demand) serve as the input data. The operation strategy of HRES is performed for an entire year, and values for the two objectives are subsequently calculated, as shown in Figure.3.

The optimisation processes repeatedly run until it reaches the specific criteria previously set as the optimisation model factor. As all possible results are shown without providing certain optimum designs, the Pareto front is a brilliant method to present them (two objectives). Then, based on the designer's aims, the best solution is selected. In this study, the population size and the number of generations is 150 pop and 50 gen, respectively. Other factors, such as crossover and mutation rate, are set to default pymoo values.

4. RESULTS AND DISCUSSION

As presented in Figures 4 and 5, (f_1, f_2) refer to the two main objectives (e.g., LPSP and LORE) that have been simultaneously minimised. The hypervolume technique and running metric are adopted indicators to show the performance of optimisation during running. The decision-making feature provided by the pymoo developer relies on the compromise programming concept. As shown in Figure .4, it was noticed that when f_2 decreases, f_1 rises. This is due to the fact that the large RES capacity covers most of the peak time when the LORE increases. It was also observed that when the LORE is 0%, the highest point of the LPSP is 10%. On the other hand, the lowest value of the LPSP is 1.58%, where the highest point of LORE is 42%. It also reveals that most of the peak times during the year began at sunset, at which the PV system stops generating electricity. As a result, it can be seen that wind energy, bioenergy and PHES are the most used renewable energy sources used during peak times. The PV system is mostly exploited to pump the water from the lower reservoir to the upper reservoir. As it could be seen from Fig.5, the best value for the two objectives regarding decomposition point is 5% and 5%, respectively. Additionally, the various decision variables, including the best value as well as other objective values, are provided in Table 1. Since the optimum Pareto front is not known, the hypervolume indicator is performed relying on set reference point [1,1], then the most significant volume between provided results and reference point considers the nearest point to the optimum result. As presented in Fig.6., the hypervolume indicator increases until reaching 2000 function evaluation, then it mostly remains constant to the end of the evaluation. The running metric indicator computes the variation space between objectives in a different generation. From Fig.7,8,9, it is evident that improvement of objective space varies slightly from generation 0 until generation 40, and then no more improvement is noticed.

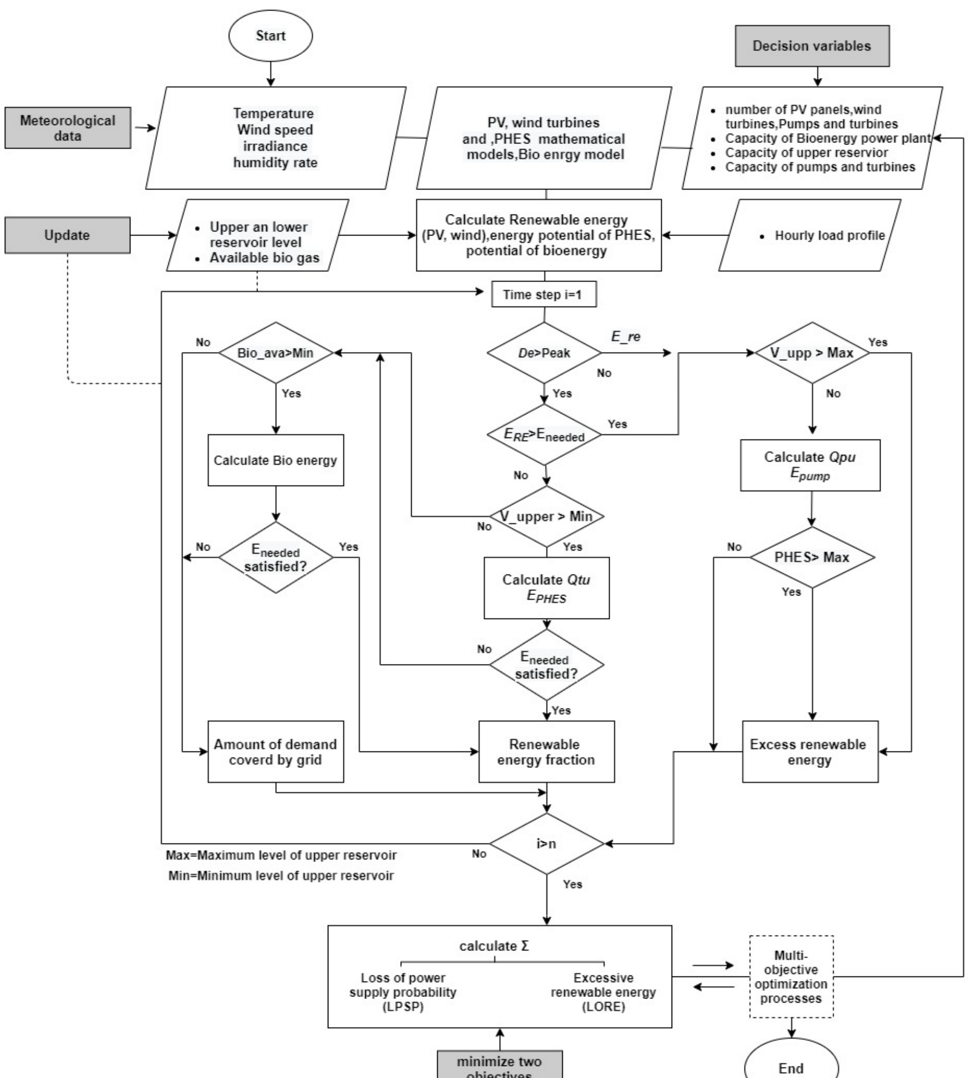

Fig.3. Flowchart of HRES operation strategy and the optimization procedure.

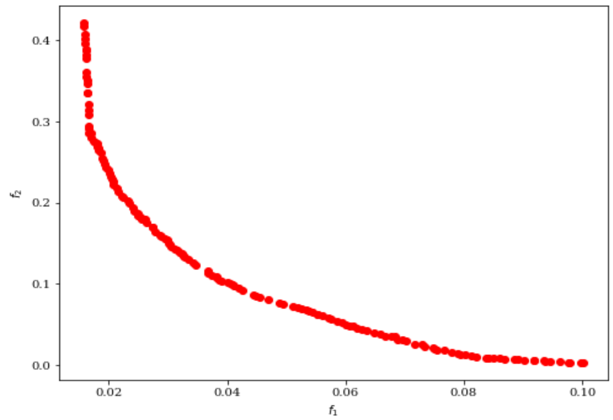

Fig.4. The Pareto front of all possible solutions for the Two objectives.

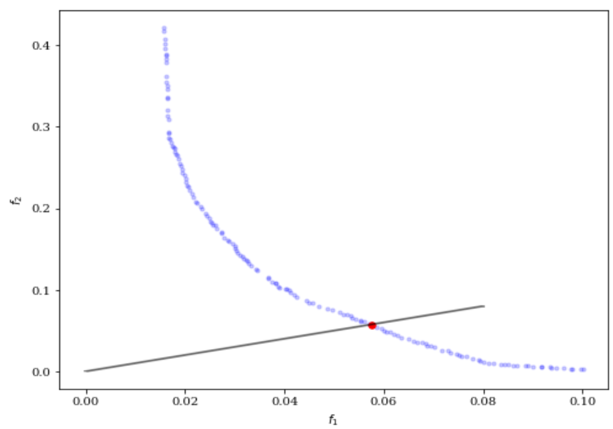

Fig.5.Optimal decomposition point, red dot refers to the compromised solution among two objectives (5%,5%).

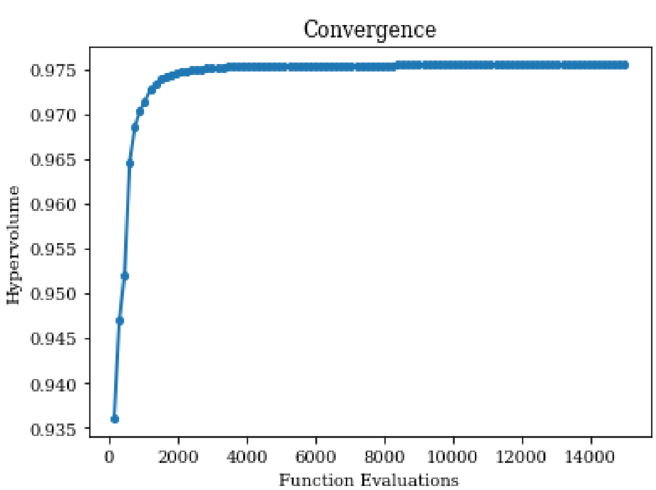

Fig.6. The Convergence of optimisation model.

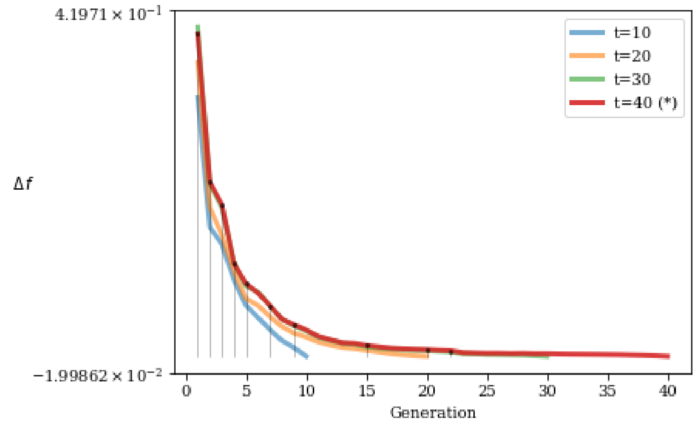

Fig.7. The running metric for generation 0-40 gen.

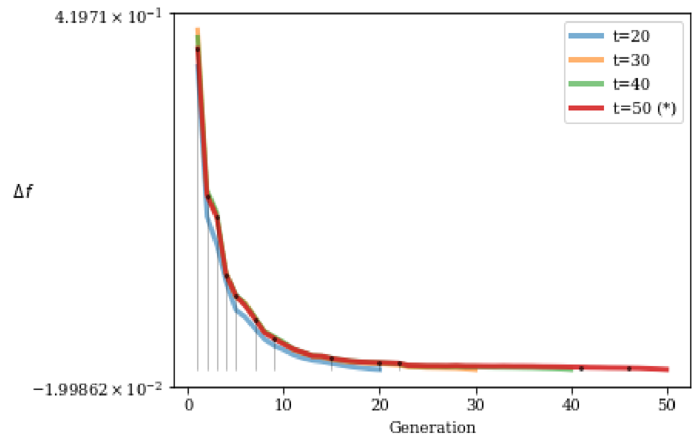

Fig.8. The running metric for generation 0-50 gen.

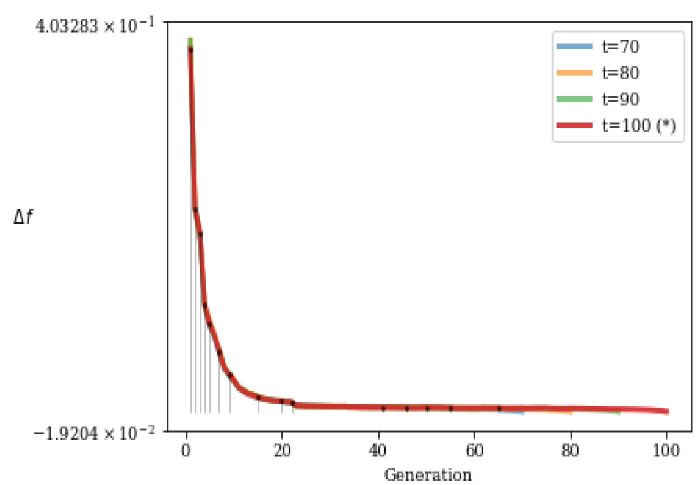

Fig.9.The running metric for generation 0-100 gen.

Table.1 Sample of some generated results.

LPSP%	LORE%	Number of PV modules	Number Of wind turbines	Number of pumps	Number of turbines	Upper reservoir capacity (Mm^3)	MSW plant capacity (MW)
10.016	0.002	1850834	75	4	4	1300000	5
4.016	10.111	2298200	86	4	4	1300000	5
2.318	20.260	2172863	148	4	4	1300000	5
1.664	30.901	2233289	200	3	4	1300000	5
1.594	40.738	2885657	200	3	4	1300000	5
1.580	42.204	2999016	200	4	4	1300000	5

5. CONCLUSION

The peak demand requires specific units to be operational during each day, and this starting and maintaining of the operation mode tend to cost more. The PV system and wind energy are not suitable to solve such a concern due to the fluctuation of natural sources. Adding a dispatchable renewable energy source (bioenergy power plant) and large-scale mature energy storage (PHES) increases the reliability of HRES in covering peak times. Then, each subsystem is separately modeled and validated against experimental results derived from literature and thus simulation tool of HRES is accomplished using Python language software. The contribution of this study is that a multiobjective optimisation model is developed by adopting NSGA2 to minimise the two main study objectives (e.g., LPSP and LORE). These objectives are employed only for peak load intervals by hybridisation both dispatchable and non-dispatchable renewable sources. The results show that the two optimal objectives values are 5% and 5%, respectively. Also, it concludes that by increasing PHES and bioenergy plant capacity, entire system dispatchability is improved.

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