MOHRES, a Software Tool for Analysis and Multiobjective Optimisation of Hybrid Renewable Energy Systems-An Overview of Capabilities

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Abstract— An overview of the functionality and general features of software tool MOHRES (Multiobjective Optimisation of Hybrid Renewable Energy Systems) and its main unique features are explained. The distinguishable capabilities include multi-criteria assessment and multiobjective optimisation, involvement of the hybrid renewable energy systems end-users in the design process, integrated size-configuration design optimisation, incorporating dispatch strategy as a function of energy management systems in design and optimisation, flexible demand load planning, and system analysis subject to uncertainties in renewable resources, demand load and power and cost modelling.

Keywords—MOHRES, HRES, hybrid renewable energy systems, multiobjective optimisation, analysis under uncertainties, load planning, end-user requirement, dispatch strategy

I. Introduction

Hybrid renewable energy systems (HRES) are made of renewable components, such as wind turbine, solar PV and fuel cell; storage components, such as battery bank and electrolyser/hydrogen tank; potentially non-renewable auxiliary or backup systems such as diesel generator; and energy management components. This makes design of HRES a complex problem. The main objective in design of a HRES is to find the most cost-effective and most reliable solution that serves a given demand load. Reliability and cost-effectiveness are, by nature, conflicting objectives. This adds another complexity to the design of HRES. Moreover, the presence uncertainties in renewable resources and demand load, if not dealt with adequately, leads to solutions which do not perform as predicted, no matter how sophisticated the system modelling and the design process are.

Amongst significant amount of reported research on different aspects of design of HRES, one particular area which the research community has been focused during the past decade has been the development of specialised software tools for design of HRES. This effort has led to the development of several tools, such as HOMER, Hybrid2, RETScreen, iHOGA, INSEL, TRNSYS, iGRHYSO, HYBRIDS, RAPSIM, SOMES, SOLSTOR, HySim, HybSim, IPSYS, HySys, Dymola/Modelica, ARES, SOLSIM, and HYBRID DESIGNER. Comparative analysis of these software tools has been the subject of a number of studies [1-5]. The results of these comparative assessments indicate that some of these tools have clear advantages and outperform the others in most of the assessment criteria. Amongst these tools, HOMER is found to be most widely used tool as it has maximum combination of renewable energy systems and performs

optimisation and sensitivity analysis [5]. However, black box coding, low-fidelity optimisation method compared to those robust methods reported in the literature, and not dealing with uncertainties adequately are the main drawbacks of this widely used tool. Moreover, improvements such as, allowing user to modify control techniques and demand load management deemed to be necessary to obtain more cost-effective and reliable solutions [5].

MOHRES, is a software tool developed by the author and his team for analysis and design of generic wind-PV -battery-fuel cell- electrolyser-diesel systems under uncertainties while incorporating the elements of energy management system (EMS), end-user requirements and load planning. The main features and a top overview of its capabilities are given in the following sections.

II. HRES Performance Analysis

Performance analysis of HRES differs from one research to another and depends on the researcher's methodological approach in cost and power modelling which is identified by the number and type of parameters used for characterisation of the system. Moreover, the performance measures which have been used to evaluate a HRES varies between different reported research. In addition, the researcher's approach in dealing with uncertainties in renewable resources, demand load, and power/cost modelling can lead to two completely different classes of analysis, namely, deterministic and nondeterministic.

A. Multicriteria Assessment via Multiple Performance Measures

MOHRES evaluates a hybrid renewable energy system in terms of a wide range of traditional and new performance measures belonging to three categories, namely, cost, reliability, and the environmental impact. These performance measures, shown by $\vec{Y}$ in Eq. 1, include: present value of the total lifespan cost (TLSC), levelised cost of energy (LCE), excess power (P_{ex}), profit by selling electricity to grid ($profit$), unmet load (P_u), total, average and maximum duration of blackout/downtime (BO_t, BO_{av}, BO_{max}), mean time between failures ($MTBF$), CO_2 emission (in case of HRES with diesel generator as backup or auxiliary power system) and renewable penetration (R_p):

$$\vec{Y} = \{TLSC, LCE, P_{ex}, profit, P_u, BO_t, BO_{av}, BO_{max}, \\ MTBF, CO_2, R_p\} \quad (1)$$

TABLE I.   UNMET LOAD VERSUS BLACKOUT DURATION AND MTBF

System	WT Rotor Radi. (m)	PV Area (m²)	N_B	TLSC (1000$)	LCE (c/kWh)	BO_t (h)	BO_{av} (h)	BO_{max} (h)	P_u (kWh)	MTBF (h)
1	2.1	169	320	117	21	264	2	2	1398	49
2	0	187	188	92	16.5	365	2	3	1401	46

B. New Reliability Measures Allow End-user Centred Design

New performance measures 'Blackout Duration' and 'Mean Time Between Failures' are unique to MOHRES and play a key role in the involvement of the end-user into the design of HRES. Unmet load is the most common parameter in evaluating a power system in terms of the reliability of the power supply. For two reasons unmet load is not a suitable parameter for evaluating the reliability of standalone hybrid systems. Firstly, it does not give tangible information to the end-user of the system. For instance, Systems 1 shown in Table I [6] has a total yearly P_u of 1398 kWh. Questions such as 'How unreliable (or reliable) is the system? How different is this from an unmet load of, for example, 1500 kW?' are typical questions that the end-user may ask. Instead, new reliability measures blackout duration and MTBF provide the end-user/customer a tangible means for understanding the reliability of the system. The 1398 kWh unmet load of System 1 is equivalent to a total yearly downtime duration of 264 hours, which occur every 49 hours in average, the average duration of downtimes is 2 hours, and no downtime duration lasts more than 2 hours. Secondly, two systems with practically the same unmet load (1398 kWh of System 1 versus 1401 kWh of System 2) can have different performance in terms of power cut behaviour as well as cost measures.

C. Deterministic and Nondeterministic Analysis

Three main sources of uncertainties affecting accurate analysis of HRES are: stochastic nature of the renewable resources, uncertainties in the parameters of the employed cost and power models, and the uncertainty in the demand load due to some level of unpredictability in human behaviour. These uncertainties make deterministic methods of analysis, which are based on averaged values, fall short in accurate analysis of the performance of HRES [7, 8].
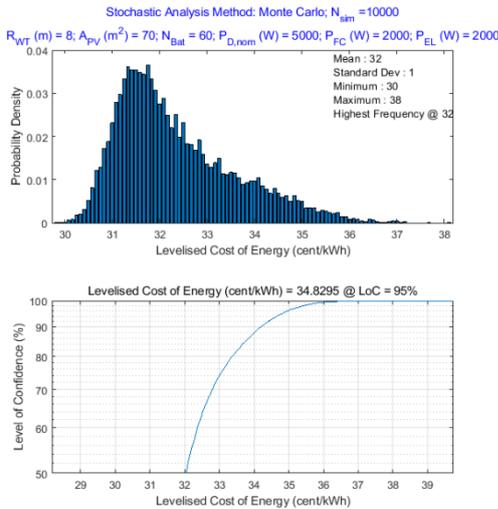
Fig. 1. An example of performance measures obtained by nondeterministic analysis: $LCE = 34.8 \frac{cent}{kWh} @ LoC\ of\ 95\%$

MOHRES, besides traditional deterministic analysis, conducts nondeterministic analysis to predict the performance of a HRES accurately. In nondeterministic analysis by employing stochastic methods such as Monte Carlo (MC), Latin Hypercube (LHC), and Antithetic MC, the uncertainties in parameters are taken into account by their probability density (PDF) functions instead of the averaged values. As a result, the performance measures are also obtained in terms of their PDF, which can be converted to cumulative density function and then translated to level of confidence (LoC). Fig. 1 shows an example of the output of MOHRES after conducting a stochastic analysis.

III. DESIGN OPTIMISATION

The HRES size optimisation method adopted by different researchers has been under the influence of their problem formulation and analysis method. For single objective optimisation cases different metaheuristic methods, including genetic algorithm (GA), particle swarm, ant colony, artificial bee colony, big bang big crunch, bee swarm, harmony search, simulated annealing, as well as hybrid methods have been applied. For multiobjective cases, metaheuristic multiobjective optimisation methods such as multiobjective GA, nondominated sorting genetic algorithm (NSGA) and multiobjective particle swarm are amongst the most popular methods.

A. Integrated Configuration and Size Optimisation Formulation

Traditionally, configuration of the system (the combination of renewable, storage and auxiliary components in the system) is decided first and then the size of each component is optimised. In many cases finding the best configuration is not a trivial task. In these cases, in traditional approach, we find the optimum component size for each possible configuration and then compare all optimum solutions against each other to find the best configuration. This could lead to solving up to 20 separate optimisation problems for a generic wind turbine, PV panel, battery bank, diesel generator and fuel cell/electrolyser system [9].

MOHRES, on the other hand, integrates the configuration optimisation and size optimisation together and conduct only one optimisation problem to find the best configuration and the best size of components for that configuration. An integrated configuration-size optimisation leads to finding superior solutions with less effort.

B. Energy Management System

Flow of energy within the system is an important matter in HRES to serve the demand load continuously and to keep the system balanced. In systems with multiple storage and auxiliary components, a dispatch strategy is needed to be implemented in the EMS. A dispatch strategy defines the order of charging of the storage systems during energy surplus period and the order of usage of storage/auxiliary systems during power deficit period. The common practice is to set the dispatch model prior to size optimisation process or test different dispatch strategies to obtain best possible output of after size optimisation.

Another unique features of MOHRES is bringing elements from EMS into design optimisation. MOHRES allows for the inclusion of the dispatch strategy in the optimisation process via two additional design variables, namely usage order O_u and charging order O_c. Fig. 2 shows the Results graphical user

interface (GUI) of MOHRES, containing the results of stochastic analysis of 12 possible dispatch strategies for a wind-PV-battery-diesel-fuel cell-electrolyser configuration.

C. Design Variables

For a generic wind turbine, PV panel, battery bank, diesel generator and fuel cell/electrolyser configuration and in the context of an integrated configuration-size optimisation with dispatch strategy also as a design parameter, the vector of the design variables in MOHRES is given by:

$$\vec{X} = \{A_{WT}, A_{PV}, n_B, P_{D,nom}, P_{FC,nom}, P_{EL,nom}, O_c, O_u\} \quad (2)$$

The first 6 design variables are size-related variables while O_c, O_u are treated differently, as they refer to an order instead of a size. In contrary to the common practice in sizing wind turbines, as in HOMER, in which the size of wind turbine is identified by its rated power, in MOHRES the size of wind turbine is defined based on its rotor area. There is a good reason behind this as explained below. The levelised cost of energy produced by a single wind turbine with a rated power of P_{rated} is less than the levelised cost of energy produced by more than one wind turbine with a similar cumulative rated power of P_{rated}. That is, in order to optimise a system with wind energy, we should be aiming at using only one wind turbine in the site, if possible. Obviously, the user can then select the closest available turbine in the market or develop the bespoke wind turbine for that site.

In the context of optimisation, we need to define the boundaries of the design space, or in other words the upper and lower bounds of each design candidate $\vec{X}^l$ and $\vec{X}^u$. The upper bound x^u for each size-related design variable is, by default, estimated by assuming that component can deliver the whole power supply for the given demand load. The default lower bound x^l for each size-related design variable is set to zero. However, the user can override both the lower and upper bounds to aim at (i) integrated size-configuration design, in which the lower bounds of all size-related design variables are set to zero, allowing for the removal of the associated component from the configuration within the optimisation process, where necessary, to achieve optimum configuration; (ii) size optimisation for a specific configuration, in which the lower and upper bounds of those components which are not included in the configuration are set to zero; (iii) retrofitting of an existing system, in which the lower bound of the existing components are set as the existing size and the upper bound, depending on whether expansion is an option or not, can be set equal to the existing size or the default upper bound; and (iv) design refinement (using a narrowed bound for any of the components). Table II shows examples of how the user can set the bounds to achieve any of the aims above.
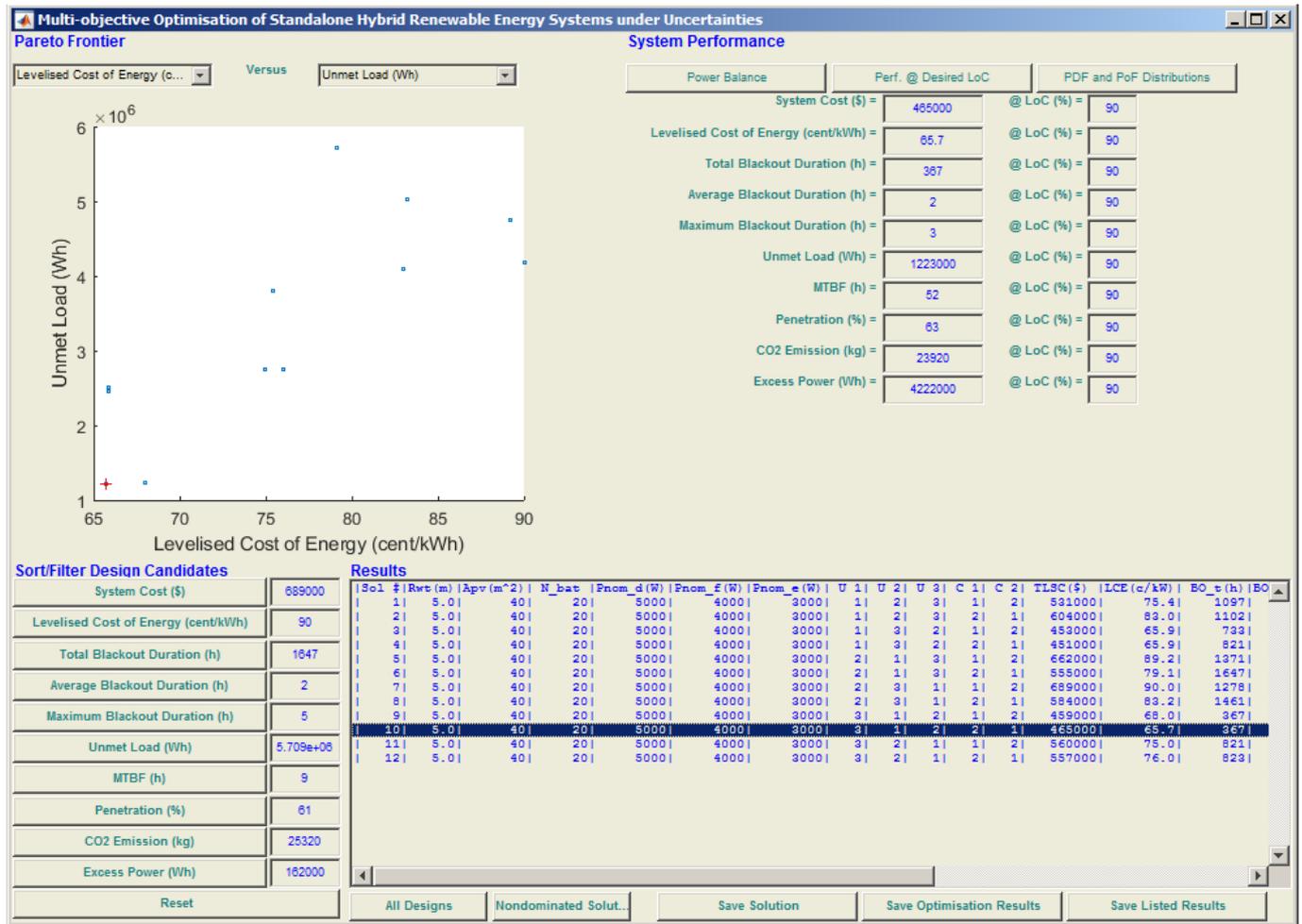
Fig. 2. MOHRES Results GUI-Effect of various dispatch strategies on the performance of a HRES with multiple storage/auxiliary components (usage and charging orders are shown in columns U1 to C2 in the Results section; numbers 1, 2 and 3, respectively, stand for battery, fuel cell and diesel generator in U columns and numbers 1 and 2 stand for battery and hydrogen tank in C comulns).

D. Single and Multiobjective Optimisation

MOHRES employs a variety of single and multiobjective heuristic and metaheuristic optimisation techniques which have been specifically developed and tailored for HRES design space. The search methods include Genetic Algorithm, Particle Swarm, Ant Colony, Heuristic, Response Surface Modelling and NSGA-II. In addition, an exhaustive search algorithm is also implemented in MOHRES which depending on the computational power available, can be used for smaller design spaces or for search refinement in the neighbourhood of optimum solutions obtained by metaheuristic methods. Any of the performance measures $\vec{Y}$ can be selected as the objective of optimisation or as a constraint.

Table III shows some examples of optimisation problems. In Example 1, 'a reliable system' can be formulated as a system with zero unmet load $P_u = 0$, or equivalently zero downtime $BO_t = 0$, or no failure occurrence for the period of analysis $MTBF = 8760 \, hr$ (for a yearly analysis). In Example 2, the constraint of a reliable system ($P_u = 0$) has been replaced with some constraints based on the end-user's requirements on the duration and frequency of downtime (blackout). In Example 3 three conflicting objectives are involved. Hence, a multiobjective optimisation is required. The Pareto solutions for Example 3 are shown in Fig. 3.

IV. LOAD PLANNING

Load planning and scheduling is another unique feature of MOHRES [10]. The electrical load is divided into two fixed and flexible pars. The flexible electrical load is mainly due to the operation of machinery. In many real-world applications, mainly industrial applications, we have some level of flexibility in the timing of machinery operation. MOHRES can deal with two types of flexible loads: (i) flexible load duration is known and (ii) flexible load duration is a function of external factors. Employing MOHRES, we can take the advantage of flexibility in loads to:

- achieve better system performance, for example, reducing the levelised cost of energy (increasing the

lifespan of the components), reducing the unmet load or increasing the excess power produced by the system and hence increasing the profit by selling it to the grid

- minimise the impact of a reduction in renewable resources on the supply in response to weather forecast (e.g. a cloudy day for systems with PV or a calm day for systems with wind turbines)

- minimise the impact of components downtime periods, whether due to scheduled maintenance or unexpected failure/fault these on the system performance

In HRES which supply energy for production and where the amount of production depends on the amount of available energy, we can also improve the overall performance by:

- increasing the production, $product$ and

- decreasing the production cost, $C_{product}$

For instance, for a standalone generic renewable-battery-diesel HRES which is used to power a production line, the vector of load planning performance measures ($\vec{Y}_{LP}$) can be defined as:

$$\vec{Y}_{LP} = \{P_u, P_{ex}, LI_{bat}, SOC_e, CO_2, product, C_{product}\} \qquad (3)$$

where, LI_{bat} is the battery bank life index and SOC_e is the state of charge of the battery bank at the end of the planning period, both to be maximised. A multiobjective load planning optimisation is formulated as:

$$min/\max \vec{Y}_{LP}(L_j(t_j)) \qquad (4)$$

subject to two sets of constraints: (i) constraints defined on the HRES performance measures (cost, reliability and environmental impact as shown in Eq. 1) and (ii) problem specific constraints defined on the flexible loads. Fig. 4 and Fig. 5 show an example of a load planning problem using MOHRES.

TABLE II. EXAMPLES OF DESIGN SPACE BOUNDARIES FOR DIFFERENT DESIGN OPTIMISATION SCENARIO

	Design optimisation scenario	Design space boundaries
1	Generic integrated size-confutation design- All components can be included in the configuration and the optimisation process eliminates those which are not cost-effective	$\vec{X}^u = \{A^u_{WT}, A^u_{PV}, n^u_B, P^u_{D,nom}, P^u_{FC,nom}, P^u_{EL,nom}\}$ $\vec{X}^l = \{0,0,0,0,0,0\}$
2	Size optimisation of a predefined configuration (here, a wind-PV-battery system)	$\vec{X}^u = \{A^u_{WT}, A^u_{PV}, n^u_B, 0,0,0\}$ $\vec{X}^l = \{0,0,0,0,0,0\}$
3	Retrofitting of an existing system (here, a wind -battery system of size A_{WT}, n_B and all other components as potential component in the configuration)	$\vec{X}^u = \{A_{WT}, A^u_{PV}, n_B, P^u_{D,nom}, P^u_{FC,nom}, P^u_{EL,nom}\}$ $\vec{X}^l = \{A_{WT}, 0, n_B, 0,0,0\}$
4	Retrofitting of an existing system with a constraint on the configuration (here, a wind -battery system of size A_{WT}, n_B and the exclusion of diesel generator as a potential component in the configuration)	$\vec{X}^u = \{A_{WT}, A^u_{PV}, n_B, 0, P^u_{FC,nom}, P^u_{EL,nom}\}$ $\vec{X}^l = \{A_{WT}, 0, n_B, 0,0,0\}$
5	Retrofitting of an existing system with the possibility of expansion (here, a PV system with a size of A_{PV} which can be also expanded)	$\vec{X}^u = \{A^u_{WT}, A^u_{PV}, n^u_B, P^u_{D,nom}, P^u_{FC,nom}, P^u_{EL,nom}\}$ $\vec{X}^l = \{0, A_{PV}, 0,0,0,0\}$

TABLE III. EXAMPLES OF SINGLE AND MULTIOBJECTIVE OPTIMISATION PROBLEM FORMULATION

	Design problem	Optimisation Formulation
1	For a given site (given renewable resources and demand load), design a reliable system which produces energy with minimal cost.	$\min\{LCE\}$ s.t. $P_u = 0$
2	Design the most cost-effective system for a given site which satisfies the following end-user requirements: no downtime duration of more than 3 hours and the frequency of downtime occurrence 2 days or more.	$\min\{TLSC\}$ s.t. $BO_{max} \leq 3 \, hr$ $MTBF \geq 48 \, hr$
3	For a given site, design the most reliable system which produces the cheapest energy with highest excess power for selling to the grid.	$\min\{LCE, P_u\}, \max\{P_{ex}\}$

Multi-objective Optimisation of Standalone Hybrid Renewable Energy Systems under Uncertainties

Pareto Frontier

Levelised Cost of Energy (c... ▼   Versus   Excess Power (Wh) ▼

System Performance

| Power Balance | Perf. @ Desired LoC | PDF and PoF Distributions |

System Cost ($) = ___   @ LoC (%) = ___
Levelised Cost of Energy (cent/kWh) = ___   @ LoC (%) = ___
Total Blackout Duration (h) = ___   @ LoC (%) = ___
Average Blackout Duration (h) = ___   @ LoC (%) = ___
Maximum Blackout Duration (h) = ___   @ LoC (%) = ___
Unmet Load (Wh) = ___   @ LoC (%) = ___
MTBF (h) = ___   @ LoC (%) = ___
Penetration (%) = ___   @ LoC (%) = ___
CO2 Emission (kg) = ___   @ LoC (%) = ___
Excess Power (Wh) = ___   @ LoC (%) = ___

Sort/Filter Design Candidates

System Cost ($)	1.422e+06
Levelised Cost of Energy (cent/kWh)	185.2
Total Blackout Duration (h)	8760
Average Blackout Duration (h)	8760
Maximum Blackout Duration (h)	8760
Unmet Load (Wh)	5.6465e+07
MTBF (h)	0
Penetration (%)	0
CO2 Emission (kg)	6150
Excess Power (Wh)	0

Reset

Results

Sol #	Rwt(m)	Apv(m^2)	N_bat	Pnom_d(W)	Pnom_f(W)	Pnom_e(W)	U 1	U 2	U 3	C 1	C 2	TLSC($)	LCE(c/kW)	BO_t(h)	BO
1	0.0	0	0	0	0	0	0	0	0	0	0	0	0.0	8760	
2	0.0	64	16	0	0	0	1	0	0	1	0	410000	17.1	7032	
3	0.0	66	18	0	0	0	1	0	0	1	0	420000	17.1	6941	
4	0.0	85	38	0	0	0	1	0	0	1	0	570000	18.4	5752	
5	0.0	102	58	0	0	0	1	0	0	1	0	690000	19.0	5202	
6	0.0	285	208	0	0	0	1	0	0	1	0	1760000	23.0	0	
7	22.0	448	0	0	0	0	0	0	0	0	0	1422000	185.2	0	
8	0.0	50	0	0	0	0	0	0	0	0	0	30000	16.0	8489	
9	20.3	14	38	200	0	0	1	3	0	1	0	1068000	139.2	0	
10	21.4	440	0	0	0	0	0	0	0	0	0	1352000	176.3	92	
11	12.1	49	10	0	0	0	1	0	0	1	0	556000	74.6	367	
12	13.2	41	18	700	0	0	1	3	0	1	0	623000	82.4	276	
13	5.7	448	20	500	0	0	3	1	0	1	0	379000	54.8	1647	
14	22.0	0	38	0	100	500	1	2	0	1	2	1244000	162.1	0	
15	0.0	124	58	0	500	100	2	1	0	1	2	88000	21.7	4928	
16	18.8	3	22	3800	0	0	3	1	0	1	0	944000	123.1	0	
17	7.3	439	6	0	0	0	1	0	0	1	0	438000	64.1	1645	
18	21.8	0	24	0	0	0	1	0	0	1	0	1216000	158.4	0	
19	15.1	124	38	0	0	0	1	0	0	1	0	779000	101.5	0	

| All Designs | Nondominated Solut... | Save Solution | Save Optimisation Results | Save Listed Results |

Fig. 3.   MOHRES Results GUI- Pareto solutions for Example 3 in Table III
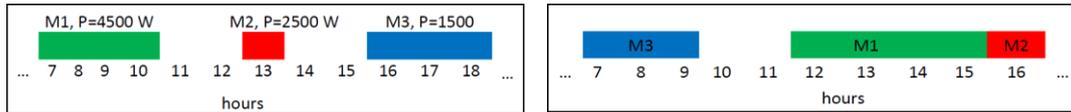
Fig. 4.   Left-Three machine operations with flexibility in operation time subject to: the operation on machine M1 must start at or after 7 am and end by 15 pm; its 4-hour duration can be split into smaller 1-hour durations; operation on machine M2 can start at any time as long as the operation on M1 is concluded; operation on machine M3 is continuous and can start either at 16 pm or 7 am. Right-Optimum machine operation schedule minimising P_u and maximising LI_{bat} and SOC_{24} subject to no unmet load ($P_u = 0$).
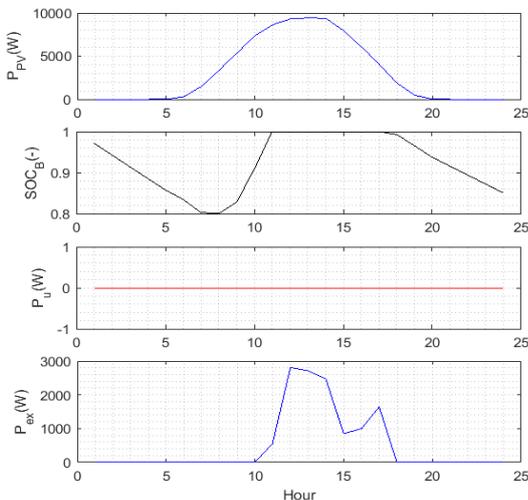
Fig. 5.   24-hour window power balance of optimum operation schedule

V.   GENERAL FEATURES

In the development of MOHRES two general attributes, namely, ease of use and ease of maintenance and further development have been considered. MOHRES, through its GUIs allows a great deal of interaction with its user, whether serving as an analysis tool, a design optimisation tool, or a decision support system. Although analysis is part of any design candidate evaluation within an optimisation process, further and detailed analysis can be also conducted upon the completion of an optimisation. For instance, once an optimisation is concluded, the user can select any of the produced solutions and conduct a detailed power balance analysis (Fig. 6), cost analysis or stochastic analysis. When dealing with multiple potential solutions (e.g. as a result of multiobjective optimisation), MOHRES, as a decision support system, facilitates shortlisting and final selection by allowing sorting and filtering the solutions (see Fig. 2 or Fig. 3, the 'Sort/Filter Design Candidates' section of the Results GUI).
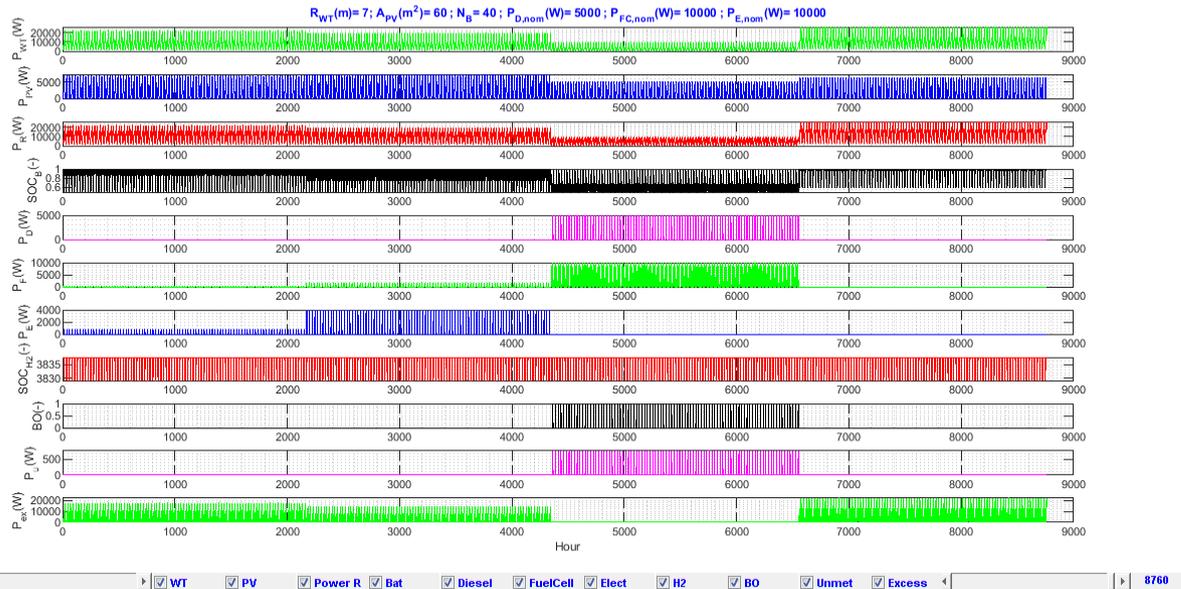
Fig. 6. A typical power balance for a wind-PV-battery-fuel cell-electrolyser/hydrohen-diesel system

MOHRES is soft-coded. A data protocol defines all necessary inputs/parameters within 15 categories, stored in a MATLAB file (called Defaults.m). As a result, one can add new features and capabilities easily. For instance, to add a new component to the generic HRES, the developer needs to add only two files for power and cost analysis of the new component in the relevant folders and modify few lines in the Defaults file (see Fig. 7). Sample case studies and more details on MOHRES general features can be found at [11].

VI. SUMMARY AND CONCLUSION

MOHRES conducts single and multiobjective size and configuration optimisation of standalone and on-grid hybrid renewable energy systems. It can deal with a generic hybrid configuration consisting of wind, PV, diesel, battery, fuel cell and electrolyser components. It employs innovative design and optimisation technique specifically developed for HRES design spaces. MOHRES is the only HRES design and analysis tool that predicts the performance of a HRES accurately by considering uncertainties in renewable resources, demand load and model parameters. It involves HRES end-users in the design process by taking into account their requirements in optimisation formulation and providing them with a set of Pareto optimal solutions to select from through a simple and straightforward process. It allows the optimisation of dispatch strategy alongside with system size and configuration optimisations and takes into account the concept of flexible and plannable demand load.

```
defaults(2).categ={'Design Variables'};
defaults(2).str={'WT Rotor Radius (m)','PV Panel Area
(m^2)','No of Batteries', 'Nominal Diesel Generator Size
(Watt)','Nominal Fuel Cell Size (Watt)','Nominal
Electrolyser Capacity (Watt)','new string'};
defaults(2).name={'r_wt','a_pv','n_bat','p_d_nom','p_fc_n
om','p_elec_nom', 'new name'};
defaults(2).val=[7,60,40,5000,10000,10000,new value];
```

Fig. 7. Part of Defaults.m file that can be easily modified to add a new component to the generic HRES configuration: `defaults(2).str` contains the name of parameters as shown on the GUIs, `defaults(2).name` is the name of the associated variables in the code, and `defaults(2).val` contains the arbitrary default values which can be editted when running MOHRES.

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