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INCORPORATING END-USER REQUIREMENTS IN DESIGN OF HYBRID RENEWABLE ENERGY SYSTEMS

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ABSTRACT

Hybrid Renewable Energy Systems (HRES) utilise local renewable resource to supply a local demand load. Traditional size optimisation methods of standalone HRES aim at finding solutions with highest reliability in power supply and producing energy at lowest levelised cost of energy (LCE). In these methods, irrespective of the actual user requirements, the highest reliability of a system is normally defined as zero unmet load. To achieve this aim, adopting a deterministic approach, concepts such as margin of safety and autonomy period are used to size storage and backup components, assuring designing reliable systems. The present study investigates the effect of actual user requirements on the design solutions. In this paper, four different sets of user requirements are considered and for each case, a standalone hybrid wind-PV-battery-diesel-fuel cell system is designed with minimum LCE while meeting the user requirements. Comparing the results with those obtained by using traditional methods show how using the proposed method can lead to more cost effective solutions.

INTRODUCTION

Ideally, a standalone hybrid renewable energy system (HRES) should be as reliable as and as cost-effective as fossil fuel and grid connected HRES power systems. This makes design and sizing of HRES a multi-objective design optimisation problem with conflicting cost-related and reliability-related objectives. For some recent published research on design optimisation of standalone HRES see [1-10].

Due to the stochastic nature of the renewable sources and the demand load, special care should be taken in designing the configuration and sizing the components to achieve a reliable system. The reliability of the system can be measured by a number of quantities such as unmet load and the loss of load probability [9]. However, it was shown in [11] that the above reliability measures used in deterministic analysis fail in producing solutions that are reliable and cost effective.

It is common practice to size the storage and backup components for worst-case scenarios, e.g. to supply the power without any renewable contribution during an autonomy period, or supplying peak load [11]. Classical deterministic design methods are aimed at designing the most reliable systems with, for example, zero unmet load. Within the optimisation process, only those solutions satisfying the hard constraint of zero unmet load are treated as feasible solutions. The optimum solution is the feasible solution with minimum cost. End user requirements are rarely discussed explicitly. A zero unmet load is defined by default an end-user requirement set on the reliability of the system. This is mainly due to the fact that the traditional reliability measures are difficult to convey to non-specialist end users.

In this study, we first define various performance measures for a HRES, which can be easily interpreted by end users. Then, we show how these can be used to design systems aiming at satisfying specific user requirements rather than achieving the highest reliability.

HRES PERFORMANCE MEASURES FROM END USER POINT OF VIEW

Performance measures of a standalone HRES can be categorised in cost-related and reliability-related measures. Cost related measures are the levelised cost of energy (LCE) as well as the cost components that form the total lifespan cost (TLSC), such as the operation and maintenance cost (fixed and variable, total and yearly), capital cost, replacement cost (total and yearly), total annual cost, etc.

Reliability related measures used mainly in traditional design optimisation methods are the unmet load and LLP. While unmet load and LLP are important assessment parameters from the designer point of view, none of them is meaningful to the end user. Hence, these parameters cannot be used to incorporate the end user requirement into the design process. Blackout duration distribution, an indication to the downtime period of the system, can be used to define three parameters the average blackout duration BO_{av}, maximum blackout period $BO_{\max}$, and total blackout time BO_t, all of them understandable by and important to end users. Another reliability measure which, compared to unmet load and LLP, is more tangible to end users is mean time between failures (MTBF).

End user requirements can be set on both reliability and cost related performance measures. Reliability requirements can be set in related to the application of the power and the tolerability of power cut. As an example of an application related we can refer to an automatic renewable-powered farm watering system. The end user requirement can be set in the form of power supply for a certain number of hours during the day. Tolerability of power cut can be addressed by the consequence of a power cut. It should be noted sizing standalone HRES is multi-objective with conflicting objectives of reliability and cost. That is, any loss on the reliability can be directed to become a gain in the cost. The number of hours of power cut, its frequency of occurrence, its average duration and its maximum duration can be used to set end user requirements.

HRES PERFORMANCE MEASURES

This section is dedicated to defining the performance measures. The capital cost is given by:

$$C_c = \sum\nolimits_{comp} C_{u,comp} S_{comp} (1 + \alpha_{ins,comp}) \tag{1}$$

in which S_{comp} is the size of the component, $C_{u,comp}$ is the unit cost and $\alpha_{ins,comp}$ is the installation cost as a fraction of the total cost of the component. The unit cost is given per nominal watt power for diesel generator, fuel cell and electrolyser; per Ah capacity for battery and per unit area for wind turbine and PV panel. The replacement cost of a component depends on the number of replacements of that component $n_{r,comp}$, as well as its capital cost as follows

$$C_r = \sum\nolimits_{comp} n_{r,comp} C_{c,comp} \tag{2}$$

For the wind turbine and PV panel:

$$n_{r,comp} = \left\lceil \frac{N_S}{N_{nom,comp}} \right\rceil \tag{3}$$

where, N_S and $N_{nom,comp}$ are the nominal life of the system and component respectively. For the diesel generator the nominal life $N_{nom,DG}$ is given as number of working hours. Assuming the total number of operation per year is T_{DG} the number of replacement can be calculated by:

$$n_{r,DG} = \left\lceil \frac{N_S T_{DG}}{N_{nom,DG}} \right\rceil \tag{4}$$

Number of replacement for the battery bank depends on its nominal life $N_{nom,B}$ as well as the equivalent life $N_{eq,B}$ which in turn depends on the number of charge-discharge cycles and the depth of discharge:

$$n_{r,B} = \left\lceil \max\left\{ \frac{N_S}{N_{nom,B}}, \frac{N_S}{N_{eq,B}} \right\} \right\rceil \tag{5}$$

$$N_{eq,B} = \frac{1}{\sum_{i=1}^{n} \frac{1}{n_{fail}}} \tag{6}$$

$$n_{fail} = 540.1 DOD_i^{-0.991} \tag{7}$$

in which, n is the number of the charge-discharge cycles of the battery bank per year. Parameter n_{fail} stands for the number of cycles to fail and is correlated to the depth of discharge DOD via Equation 7 for the type of the battery used in this study.

Finally, the last component of traditional cost measures is operating and maintenance. It is divided into fixed and variable parts:

$$C_{O\&M} = \sum\nolimits_{comp} C_{O\&M,F,comp} + \sum\nolimits_{comp} C_{O\&M,V,comp} \tag{8}$$

where,

$$C_{O\&M,F,comp} = \alpha_{O\&M,comp} C_{c,comp} \tag{9}$$

$$C_{O\&M,V,DG} = \frac{0.246\sum_{i=1}^{8760} P_{h,DG_i} + 0.08145 P_{DG,nom} T_{DG}}{1000} C_{fuel} \quad (10)$$

in which P_{h,DG_i} is the hourly-averaged diesel power and C_{fuel} is the price of fuel. The variable part for renewable sources, fuel cell, electrolyser and battery bank is zero.

Total lifespan cost (TLSC) analysis considers all the traditional costs over the lifespan of the product:

$$TLSC = \sum_{j=0}^{N_S} \frac{c_j}{(1+dr)^j} \quad (11)$$

where, dr is the annual discount rate, N_S is the lifespan of the system, c_j is the sum of all cost components in year j.

In systems with constant annual output over the lifespan the LCE is given by

$$LCE = \frac{TLSC}{AEO} UCRF \quad (12)$$

in which, AEO is the annual energy output and UCRF is the uniform capital recovery factor given by:

$$UCRF = \frac{d(1+d)^{N_S}}{(1+d)^{N_S} - 1} \quad (13)$$

In case of standalone systems, where the excess power is dumped, the AEO is replaced with the usable amount of produced energy. Table 1 shows the parameters used for the cost analysis in this paper [9, 12].

TABLE 1-COST PARAMETERS

	WT	PV	BB	DG	FC	E
S	$A_{WT}(m^2)$	$A_{PV}(m^2)$	$n_B c_B(Ah)$	$P_{DG,nom}$	$P_{fc,nom}$	$P_{elec,nom}$
C_u	480 \$/m²	830 \$/m²	1.5 \$/Ah	0.4\$/W	4.08\$/W	2\$/W
α_{ins}	0.2	0.4	0	0	0	0
$\alpha_{O\&M}$	0.03	0.01	0.01	0.15	0.1	0.1
N_{nom}	25 years	25 years	4 years	15000 hours	30000 hours	20 years
$C_{O\&M}$	0	0	0	C_{fuel} = 1\$/l	0	0

As defined in [11] the reliability performance measures MTBF, total unmet load U_t and blackout distribution are given as:

$$MTBF = \frac{\sum_{i=1}^{8760} \max\left\{0, sign\left(\left(\overline{P}_{h,a}/\overline{L}_h\right)_i - 1\right)\right\}}{N_{fail}} \quad (14)$$

$$U_t = U \sum_{i=1}^{8760} \left(\overline{L}_h\right)_i \quad (15)$$

$$BO_i = \max\left\{0, sign\left(1 - \left(\overline{P}_{h,a}/\overline{L}_h\right)_i\right)\right\} \quad (16)$$

where, $sign(\cdot)$ is the sign function, N_{fail} is the number of blackout occurrences during period T =1 year=8760 hour, $\overline{L}_h$ is the hourly-averaged load, $\overline{P}_{h,a}$ is the hourly averaged usable available power, and U in Equation 17 is the unmet load given by:

$$U = \frac{1}{8760} \sum_{i=1}^{8760} \left(1 - \overline{P}_{h,a}/\overline{L}_h\right)_i , \quad (17)$$

Usable available power is defined as:

$$P_a = \min\{P_{t,a}, L\} \quad (18)$$

where, $P_{t,a}$ stands for the total renewable and non-renewable available power.

RESULTS AND DISCUSSION

In this section, five different cases are studied. For each case, the optimum system configuration and the optimum size of system components are obtained satisfying the user requirements defined on reliability and/or cost measures. Optimisation is based on a deterministic exhaustive search. The resource and load profile are adopted from [13]. In the first case study, (C1), storage and backup components (battery bank, diesel generator and fuel cell) are sized using a margin of safety (MoS) and an autonomy period T_a. In the rest of case studies the storage and backup components are sized along with other renewable components within optimisation process. Tables 2 and 3 show the optimum systems and their performance for each case respectively.

Case Study 1 (C1)

For this case, we aim at finding the most cost effective fully reliable solution ($U_t = 0$, $BO_t = 0$, $BO_{av} = 0$, $BO_{\max} = 0$, $MTBF = 8760\ hour$). Size optimisation of battery bank, diesel generator and fuel cell is based on autonomy period and margin of safety. Using the common values of autonomy period of one day and MoS of 20%, the size of storage and backup components can be found using:

$$P_{DG,nom} = \frac{\overline{L}_{d,\max}(1+MoS)}{24\eta_{DG}} \quad (19)$$

$$P_{FC,nom} = \frac{\overline{L}_{d,\max}(1+MoS)}{24\eta_{FC}} \quad (20)$$

$$N_B = \frac{T_a \overline{L}_{d,\max}(1+MoS)}{bc_B V_B} \tag{21}$$

where $\overline{L}_{d,\max}$ is the maximum daily averaged demand load, η_{DG} and η_{FC} are diesel and fuel cell efficiencies respectively, and bc_B and V_B are the battery unit nominal capacity and the battery bank voltage. It should be noted, since the system is using more than one back-up and or storage component, the sizing is based on daily average values instead of daily peak values. This leads to smaller nominal sizes and therefore, reduction in the cost [11].

The results show that the largest contribution of power is from diesel generator, followed by the fuel cell. In this case, the system is fully reliable. In other words, there is no blackout or unmet load and the mean time between failures is 8760 hours. It should be noted that this case is the most common practice when seeking for full reliability.

Case Study 2 (C2)

For this case, similar to case C1, we are looking for the most cost effective fully reliable solution ($U_t = 0$, $BO_t = 0$, $BO_{av} = 0$, $BO_{\max} = 0$, $MTBF = 8760$). However, size optimisation of battery bank, diesel generator and fuel cell is alongside other components. As it can be observed in Table 2, in this case study, the system is fully reliable, there is no nominal power contribution from diesel generator and the fuel cell, *LCE* is less than the half compared to case C1.

Case Study 3 (C3)

In this case study, we are seeking design of a HRES according to the following end user perception of reliability and requirements. The end user is aware of the high cost of a fully reliable system. He/she therefore is ready for some sacrifice on the reliability. The user can tolerate the power cut of up to two hours as long as the frequency of occurrence is low, say every two days. In this case, the end user requirements are set as $BO_{\max} \le 2hr$ (no power cut lasting more than 2 hours) and $MTBF \ge 48\,hr$ (the average time between power cuts less than two days). Compared to the case C2, tolerated failure of the system by the end user can save him/her about \$19000 in TLSC and ~3cent/kWh in LCE.

Case Study 4 (C4)

For this case study, the end user requirements are defined on blackout durations only. The end user can tolerate one hour of power cut per day in average as long as no blackout takes longer than 3 hours. This is equivalent to of a total blackout of 365 hr per year $BO_t \le 365hr$ and $BO_{\max} \le 3hr$.

Comparing C3 and C4, it is difficult to say which one is more reliable. Depending on the reliability measures used C4 can be as reliable as C3 (in terms of the average blackout duration and unmet load) or slightly less reliable as C3 (in terms of other reliability measures). It should be noted that unmet loads of 1398 kW and 1401 kW are practically the same. However, the cost of C4 is significantly less than the cost of C3. TLSC decreases by \$25,000 per year and LCE by 4.5cent/kWh.

Comparing C3 and C4 proves the point of why unmet load is not a good reliability measures. Two systems of C3 and C4 have the same unmet load but are very different in terms of both cost (TLSC of \$117000 versus \$92000 and LCE of 21c/kWh versus 16.5 c/kWh) and actual performance from the end user point of view.

Case Study 5 (C5)

In this case the end user has a hard constraint on the total lifespan cost of the system. In other words, he/she wants to have the best system that can be installed and operated with a limited budget say \$90,000. Here the cost is the only user requirement set as constraint.

It worth mentioning that, when comparing solutions C4 and C5, one can notice that the two solutions are very close in terms of cost measures. In fact C4 has violated the constraint of C4 only slightly by about 2%. But the unmet load is about 42% higher than solution of C4.

TABLE 2- OPTIMUM SYSTEMS

Case	WT Rotor Radius (m)	PV Area (m^2)	N_B	$P_{DG,nom}$ (W)	$P_{FC,nom}$ (W)	$P_{E,nom}$ (W)
C1	0	54	10	14600	12400	1100
C2	2.6	185	210	0	0	0
C3	2.1	169	320	0	0	0
C4	0	187	188	0	0	0
C5	0	182	222	0	0	0

TABLE 3- PERFORMACE MEASURES

Case	TLSC (1000\$)	LCE (c/kWh)	BO_t (h)	BO_{av} (h)	BO_{max} (h)	Unmet Load (kW)	MTBF (h)
C1	306	52.8	0	0	0	0	8760
C2	138	23.9	0	0	0	0	8760
C3	117	21	264	2	2	1398	49
C4	92	16.5	365	2	3	1401	46
C5	90	16.3	453	2	4	2007	46

CONCLUSION

Unmet load is the most common parameter in evaluating a power system in terms of the reliability of the power supply. In this paper it is shown that unmet load is not a suitable parameter for evaluating the reliability of standalone hybrid systems for two reasons. Firstly, it is difficult to understand by the end users; secondly it cannot be linked to the duration and frequency of power cut. On the other hand, parameters such as total, average and maximum blackout duration and mean time between failures can be easily interpreted by end users in terms of the amount and the frequency of the power cut. Secondly, two systems with practically the same unmet load can have different performance in terms of power cut behaviour as well as cost measures.

Introducing blackout distribution as a new performance measure makes it possible to design HRES while incorporating the requirement of end user.

NOMENCLATURE

A	Area (m^2)
AEO	Annual Energy Output
BB	Battery bank
DG	Diesel generator
E	Electrolyser
FC	Fuel cell
PV	Photovoltaic
WT	Wind Turbine
BO	Blackout Duration (hr)
C	Cost($)
bc	Battery Capacity (Ah)
dr	Discount Rate
DOD	Depth of Discharge
HRES	Hybrid Renewable Energy System
L	Demand Load(W)
LCE	Levelised Cost of Energy
LLP	Loss of Load Probability
LPSP	Loss of Power Supply Probability
MTBF	Mean Time Between Failure
N	Lifespan, Number
n	Number
P	Power (W)
TLSC	Total Life Span Cost
U	Unmet Load
UCRF	Uniform Capital Recovery Factor
V_B	Battery Bank voltage
η	Efficiency

Subscripts

a	Annual; Autonomy
av	Average; Available
B	Battery
c	Capital
DG	Diesel
d	Daily
E	Electrolyser
Eq	Equivalent
F	fixed
FC	Fuel cell
h	Hourly
ins	Installation
max	Maximum
min	Minimum
nom	Nominal
O&M	Operation and Maintenance
PV	Photovoltaic
R	Renewable
S	System
t	Total; Time
u	Unit
V	Variable
WT	Wind Turbine

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