



## Study of optimization design criteria for stand-alone hybrid renewable power systems

M. Martínez-Díaz<sup>1</sup>, R. Villafafila-Robles<sup>2</sup>, D. Montesinos-Miracle<sup>1</sup> and A. Sudrià-Andreu<sup>1,2</sup>

<sup>1</sup>Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya. ETS d'Enginyeria Industrial de Barcelona, Av. Diagonal, 647, Pl. 2. 08028 Barcelona, Spain  
Tel: +34 934016727, Fax: +34 934017433,  
e-mails: [mardiamar@gmail.com](mailto:mardiamar@gmail.com), [roberto.villafafila@citcea.upc.edu](mailto:roberto.villafafila@citcea.upc.edu), [montesinos@citcea.upc.edu](mailto:montesinos@citcea.upc.edu), [sudria@citcea.upc.edu](mailto:sudria@citcea.upc.edu)

<sup>2</sup>Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya. EU d'Enginyeria Tècnica Industrial de Barcelona, Comte d'Urgell, 187. 08036 Barcelona, Spain  
Tel: +34 934137432

### Abstract

Hybrid renewable power systems integrate two or more sources of energy, one of which is renewable, optionally a storage system and typically work in stand-alone mode. They are being considered more and more and we should increment their usage taking advantage of their positive benefits: free of charge resource availability, CO<sub>2</sub> emissions reductions and subsidies. Dealing with their inconveniences: variability of renewable resources availability and cost acquisition, through the optimization of the design and the control of the system.

The optimal design of hybrid renewable power systems is usually defined by economic criteria. But there are also technical and environmental criteria to be taken into account to improve decision-making. In this paper a discussion on different criteria will introduce the non-economical perspectives in addition to the economic criteria.

A case study of a PV-Wind-Diesel-Battery system for a Telecommunication station in Catalonia is discussed. Availability of renewable energy sources is obtained with RETScreen and PVSyst. Analysis and simulations of various hybrid power systems have been done in HOMER resulting on a comparison of different scenarios.

Optimal scenario taking into account the best results of all three types of criteria: economic, technical and environmental, is a trade-off of the economic optimum.

### Key words

hybrid renewable power system, stand-alone, optimization, design, case study.

### 1. Introduction

Energy consumption is increasing in the world, as well as human population. It is currently estimated that

approximately 2 billion people (more or less one third of the world population) do not have access to electric power [1]. The lack of energy/electric power (usual in isolated communities or in developing countries) is a barrier to economic and social development.

Current stand-alone power systems are diesel generators [1] that present many inconveniences, such as: fluctuations and uncertainties in an increasing fuel price, CO<sub>2</sub> emissions, acquisition cost of diesel generators, operation and maintenance costs, inefficiency, advanced age of the facilities, diesel transport, lack of subsidies, penalties for CO<sub>2</sub> emissions, etc.

Hybrid renewable power systems integrate two or more sources of energy, one of which is renewable, optionally a storage system and typically work in stand-alone mode [1],[2],[8]. To introduce renewable energy sources in hybrid power systems we also have to deal with the following disadvantages: renewable resources availability in different locations, intermittency, unpredictability, multiple economic and technical optimization criteria, unquantifiable environmental benefits, etc. The optimization of the design and control of stand-alone hybrid renewable power systems will enable their implementation and successful integration of renewable power sources off-grid.

### 2. Design and model

In order to design stand-alone renewable hybrid power systems there are four main aspects to be considered:

- the demand/load characterization,
- the potential of renewable and conventional energy generation,
- the restrictions of the system, and
- the optimization criteria.

To describe the demand/load side an estimation of the load is necessary and its variability through time (hours, day/night, month of the year). Whether there are critical loads or not and the reliability that requires the system.

The potential of renewable resources can be estimated with statistical data taking into account the location, the weather conditions and other environmental variables available. Much research is done in this field in order to estimate this renewable potential. The potential of conventional energy generation is defined by the fuel based technologies available (mainly diesel generators) or the possibility of connection to the grid.

Within the restrictions of the systems there's a wide range of aspects to be considered: the size of the facilities (potential limitation of renewable technologies), the conditions of uninterruptibility (some loads can be disconnected or not if they are considered as critical), the need to compensate reactive power, power quality, losses of the system, etc. Moreover, the possibility to be connected to the grid or not would define the storage requirements and redundancy systems eventually to guarantee the isolated function mode.

The optimization criteria (objective function) considered are mainly economic aspects: Net Present Cost (NPC) and Cost Of Energy (COE) typically [1]. Also technical variables and environmental factors define the configuration of the system and consequently its performance and viability. Different optimization criteria are discussed below.

### 3. Optimisation Criteria

Up to now, the wide-range of variables that influence the design [2] and control of hybrid renewable power systems and the available design tools suggests that there is a relevant need to improve the research conducted in this field.

The objective of this paper is to achieve a better understanding of how different criteria define the optimal configuration in the design of hybrid renewable power systems.

We've defined three main groups of optimization criteria: economic, technical and environmental, where we have multiple potential criteria in each one to be analyzed:

- economic aspects: Net Present Cost (NPC), Cost Of Energy (COE) and Interest Rate;
- technical variables: Supply reliability, Battery throughput, State of Charge of the batteries (SOC), Rate of charge of the equipment, Excess of Electricity (EoE) and Grid connection requirements if available; and
- environmental factors: Renewable Fraction (RF), CO2 emissions and site conditions. Others less studied are related to the legal framework and the subsidies/penalties associated with the generation technologies or differences among countries.

After defining the criteria to be included, the main optimization principle in the objective function might be as diverse as: minimum cost, maximum financial viability, minimum CO2 emission, minimum investment and/or maintenance cost (through life cycle analysis), minimum annual fuel cost, maximum continuity of supply, unmet load, etc.

In addition to the static design analysis, several of these criteria are dynamic through time. In order to assure the optimal design of the system different **scenarios** must be considered.

In order to understand how these different criteria contribute to the design of an optimal system, a case study is proposed based on different scenarios for a stand-alone PV-Wind-Diesel-Battery system.

### 4. Case Study

The proposed case study analyses different scenarios for a stand-alone PV-Wind-Diesel-Battery system for a Telecommunication Centre in Catalonia.

To construct these different scenarios we use the HOMER energy modeling software [3], which uses the NPC (Net Present Cost) to optimize the system design in each scenario.

The model and restrictions of the system (PV-Wind-Diesel-Battery) and the load are defined following next steps:

- A. Characterization of the load
- B. Generation technologies
- C. Availability of various energy sources
- D. Storage system
- E. Energy model

#### A. Characterization of the load. *Telecommunication Centre*

One of the applications of stand-alone hybrid power systems is in telecommunications when the connection to the grid is not feasible. These installations demand reliability [4] and robust equipment [5]. Some of these installations are operating since the 80's in sites like the Antarctica and the Arctic Circle, as well as in Canada and United States, as published by Paul Gipe [5]. Main advantages of these systems in telecommunications installations [4] are: reduction of fuel consumption and CO2 emissions, decrease of logistic and operational costs and cost effective component sizing.

Generally, Information and Communication Technology (ICT) systems are considered as a critical load, because they operate day and night. They need continuous uninterrupted service, high reliability and high quality [4] of electrical energy for telecommunication infrastructure and services.

The European Commission [6] called on Europe's information and communication technologies (ICT) industry to become 20% more energy efficient by 2015.

ICT equipment and services alone account for about 8% of electrical power used in the EU and about 2% of carbon emissions. But using ICT in a smart way could help to reduce energy consumption in energy-hungry sectors such as buildings, transport and logistics, and to save 15% in total carbon emissions by 2020. Due to the new power and energy context such as greenhouse effect and other environmental issues, fuel depletion and electricity cost increase. New regulation and standards, telecom operators have to make efforts for using renewable energy solution [8].

The proposed load is a Telecommunication Center (ICT Center). The ICT Center is located in the province of Tarragona in Catalonia at an altitude of 1.202m. With location information of the site, it is possible to determine the availability of renewable energy resources (solar and wind) for the ICT Center.

### B. Generation Technologies

Review reveals that over the last decades, hybrid renewable energy systems (HRES) applications are growing rapidly and HRES technology has proven its competitiveness for remote area applications [8]. Reviewed literature [9] reports studies on hybrid PV/wind energy system (56%), followed by Hybrid PV energy systems (23%), and Hybrid Wind energy system (21%). Other possible hybrid combinations inclusive of hydro, biomass, fuel cell, municipal waste and combined heat and power are still in development and research phase only.

For this case study we simulate a PV-Wind-Diesel system, as these are the most relevant generation technologies nowadays for hybrid systems as far as they are the most prevalent available in the market [1], [9].

### C. Availability of renewable energy sources

One of the first steps in order to study hybrid renewable power systems is to have information about the availability of energy sources, both renewable (sun, wind and water mainly) and conventional (fuel).

The literature review shows that there are different ways to obtain this information: real data from a meteorological station in the site or close, general public databases or estimation of through probabilistic models. There are many sources for solar radiation and wind speed data but we have used two very popular: RETScreen [10] and PVsyst [11].

For this case study, RETScreen software provides the meteorological data for the city of Tarragona. PVsyst software that provides more accurate meteorological data to be introduced on the energy model in HOMER. All these software tools are freeware available on internet.

### D. Storage system

Energy Storage is being widely regarded as one of the potential solutions to deal with the variations of variable electricity sources (VRES). In concrete, Electrical Energy

Storage (EES) technologies are studied in [12]. For mitigate the variability of renewable electricity sources. We evaluate the impact of VRES on power systems with respect to power quality, regulation, load following, unit commitment, and seasonal storage timescales [13]. To account for the distributed nature of VRES, capacitors, flywheels, superconducting magnetic energy storage and most batteries (except for lead-acid) are suitable because they are scalable, modular, durable, and low maintenance [13].

In general, several criteria are analyzed when considering and choosing EES technologies for a specific application: lifetime, life cycle, power and energy, self-discharge rates, environmental impact, cycle efficiency, capital cost, storage duration, and technical maturity [13].

A literature review [14] shows that batteries are the dominant technology to be used when continuous energy supply is paramount, while technologies such as flywheels and supercapacitors are more suited to power storage applications and where very brief power supply is required such as in uninterrupted power supply requirements. Lithium-ion batteries are becoming increasingly important and have several advantages over the traditional lead-acid batteries.

Finally, after these steps first the decision for the design of the model is taken. This case study will simulate a PV-Wind-Diesel-Battery system.

### E. Energy model. HOMER

The complete defined energy model: stand-alone PV-Wind-Diesel-Battery system, is defined in HOMER (see Fig. 1).

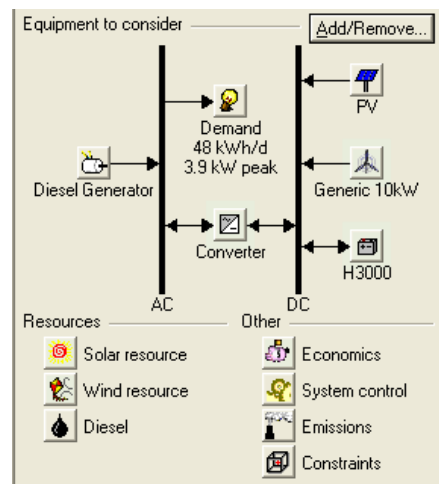


Fig. 1. Model definition in HOMER including: load, generation equipment, transformation equipment, resources available and other constraints

A first sensitivity analysis using HOMER is analyzed (see Fig. 2). The sensitivity analysis helps to reveal how changes in inputs affect the design and viability of the system. Different scenarios are proposed depending on:

- a range of minimum renewable fraction (% renewable energy/renewable versus conventional energy); and
- the availability of renewable resources (solar and wind).

These key criteria are studied because for a critical load the unpredictability of renewable resources is a constraint for the system design.

As seen in Fig. 2, the sensitive variables values that defined the scenarios are:

- 0%, 20% and 40% of Renewable Fraction
- 2,6 kWh/m<sup>2</sup>/d and 5,09 kWh/m<sup>2</sup>/d annual average of daily radiation

The hybrid systems that appears as optimal in this design space are:

- PV-DG-Battery
- Wind-DG-Battery
- Wind-PV-DG-Battery

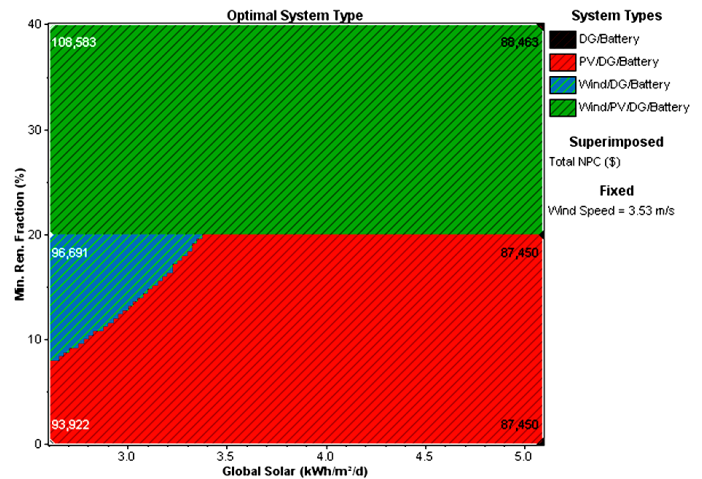


Fig. 2. Optimal Design Space for the sensitive variable values: “Renewable Fraction” and “Annual average of daily radiation”.

POWER SYSTEMS		ENERGY MODEL				OPTIMISATION CRITERIAS					
		CONV. GENERATION	RENEWABLE GENERATION		STORAGE	ENVIROMENTAL		ECONOMICAL		TECHNICAL	
		Diesel Generator	PV	Wind Turbine (10kW)	Battery (3000 Ah)	Ren. Fraction	CO2 Emissions	Total NPC	COE	Battery Throughput	Excess Electricity
		kW	kW	units	units	%	kg/yr	€	€/kWh	kWh/yr	kWh/yr
NOT RENEWABLE	DIESEL_BATTERY	2			12	0.00	14,241	93,922	0.468	1,511	0
	DIESEL_BATTERY	5	0.000	0	0	0.00	19,565	126,547	0.630	0	2
	DIESEL	5			0	0.00	19,565	126,547	0.630	0	2
HYBRID RENEWABLE	PV_DIESEL_BATTERY	2	2.160	0	12	0.25	11,292	87,45	0.436	1,945	68
	PV_DIESEL_BATTERY	2	4.320	0	12	0.47	9,46	88,463	0.441	6,345	116
	PV_WIND_DIESEL_BATTERY	2	0.135	1	12	0.27	11,596	96,616	0.481	1,961	1,277
	WIND_DIESEL_BATTERY	2	0.000	1	12	0.26	11,727	96,691	0.482	2,016	1,203
	PV_WIND_DIESEL_BATTERY	2	4.320	1	12	0.64	7,945	97,012	0.483	6,071	2,508
	PV_DIESEL_BATTERY	5	2.160	0	0	0.25	17,347	124,722	0.621	0	536
	PV_WIND_DIESEL_BATTERY	5	0.135	1	0	0.27	17,64	133,791	0.667	0	1,787
	WIND_DIESEL_BATTERY	5	0.000	1	0	0.26	17,766	133,833	0.667	0	1,735
	PV_DIESEL_BATTERY	5	4.320	0	0	0.42	16,343	128,892	0.642	0	3,493
	PV_WIND_DIESEL_BATTERY	5	2.160	1	0	0.45	16,113	134,879	0.672	0	3,33

Fig. 3. Scenarios with the different “optimization criteria” for each optimization aspect: economic, technical and environmental. Two worst cases are marked in red and two best ones in green, resulting in three optimal scenarios: A, B, C.

## 5. Scenarios and discussion

The optimal criteria selection determines different optimal design for the hybrid renewable power system.

In Fig. 3, we have the energy models simulated including relevant information of the system configuration: DG (kW), PV (kW), Wind (units of 10kW) and Battery (units of 3.000Ah). After being simulated in HOMER, the values of all optimization criteria are obtained for each configuration. The selected optimization criteria are described below.

Among economic criteria, NPC is the unique one used by HOMER software. It also provides the value of COE. As mentioned before, HOMER does not take directly into account in the optimization technical or environmental aspects but we have values of different criteria are obtained in the simulations.

Regarding technical criteria: Battery throughput and Excess of electricity (EoE) are analyzed. Battery throughput should be maximized to install a bank of batteries as a relevant active part of the system. The objective is not to oversize the storage system and negatively affect the economical results of the system. In a similar way, the EoE should be minimized for the same reason.

Environmental criteria analyzed are: the maximum renewable fraction and the minimum CO2 emissions, are correlated.

In Fig. 3, for each optimization criteria: economic, technical and environmental, the two worst cases are marked in red and two best ones in green, resulting in three optimal scenarios: A, B, C. Follow below the discussion of the main results of these three different scenarios analyzed in HOMER.

### A. Economic criteria

Prioritizing the economic criteria (both NPC and COE) the scenario A is the optimal one: PV (2,16kW) - Diesel (2kW) - Battery (12x3.000Ah). It produces energy at 0,436€/kWh. It represents a renewable fraction of 25%.

### B. Technical and Environmental criteria

The prioritization of the technical criteria does not conclude any relevant optimal scenario in this case study.

Prioritizing the environmental criteria (renewable fraction and CO2 emissions) the scenario B is the optimal one: PV (4,32kW) – Wind (10kW) – Diesel (2kW) - Battery(12x3.000Ah). It represents a renewable fraction of 64%, better scenario than A. The COE is 0,483€/kWh, more expensive than A.

### C. Discussion. Better multi-criteria scenarios.

Finally, if we take a global overview of all analyzed criteria we realize that the system that combines better indicators is: Scenario C: PV (4,32kW) – Diesel (2kW) – Battery (12x3.000Ah). It represents a renewable fraction of 47%, better scenario than A. The COE is 0,441€/kWh, cheaper than B scenario.

In this scenario, with an increase of 1,1% in the optimum cost the system increases 88%, almost double, the fraction of renewable resources up to 47%. See Table I below.

Table I. – Key criteria per scenarios and % of variation from the optimum cost (Scenario A)

Key criteria:	Scenario A	Scenario B	% ΔB-A	Scenario C	% ΔC-A
NPC	0,436 €/kWh	0,483 €/kWh	10,8%	0,441 €/kWh	1,1%
Ren. Fraction	25 %	64 %	156,0%	47 %	88,0%

### D. Other applications

The study of renewable hybrid power systems are relevant for stand-alone applications, as the telecommunication center studied. In the future they'll also be of interest for facilities connected to the grid that could work in islanded mode.

Other applications working in stand-alone mode, like telecommunication centers, are in healthcare facilities. In [9] authors study and design of a complete stand-alone photovoltaic (PV) system for providing the electrical loads in an emergency health clinic. Also islands and installation in villages with seasonable demand like tourism are a common studied application with hybrid power systems [10].

## 6. Conclusion

Methodology for the design of hybrid renewable power systems depending on availability of energy sources and load characteristics is needed. After the review carried out,

further research is also needed in multi-objective optimum designs in hybrid systems [14].

The importance of considering other criteria besides the cost is clear. In the analyzed case study, an increase of only 1% in the optimum cost the system almost double the fraction of renewable resources up to 47%.

## Acknowledgement

Our acknowledgement to the PhD School of KIC InnoEnergy and the European Institute of Technology (EIT) for supporting part of this research.

## References

- [1] Mir-Akbar Hessamin, Hugh Campbell, Christopher Sanguinetti, "A feasibility study of hybrid wind power systems for remote communities", Energy Policy (accepted November2010).
- [2] Sreeraj, E.S. et al., "Design of isolated renewable hybrid power systems". Sol. Energy (2010).
- [3] HOMER: Energy Modeling Software for Hybrid Renewable Energy Systems (<http://www.homerenergy.com/>), from the National Renewable Energy Laboratory (NREL) ([www.nrel.gov](http://www.nrel.gov)) of the U.S..
- [4] E. F. F. Ribeiro, A. J. Marques Cardoso and C. Boccaletti, "Uninterruptible Energy Production in Standalone Power Systems for Telecommunications", International Conference on Renewable Energies and Power Quality (ICREPQ'09), April 2009
- [5] Paul Gipe, "Wind Power. Renewable energy for Home, Farm and Bussiness", March 2004, Pages: 241-242. ISBN 978-1-931498-14-2.
- [6] European Commission Report, IP/09/1498, Brussels, 9 October 2009.
- [7] ETSI Technical Report ETSI TR 102 532, The use of alternative energy solution in telecommunication installation.
- [8] Amal A. Hassan, Abd El-Shafy A. Nafeh, Faten H. Fahmy and Mohamed A. El-Sayed, "Stand-Alone Photovoltaic System for an Emergency Health Clinic", International Conference on Renewable Energies and Power Quality (ICREPQ'10), March 2010.
- [9] M.K. Deshmukh, S.S. Deshmukh, Modeling of hybrid renewable energy systems, Renewable and Sustainable Energy Reviews, Volume 12, Issue 1, January 2008, Pages 235-249.
- [10] RETScreen: Clean Energy Project Analysis Software ([www.retscreen.net](http://www.retscreen.net)).
- [11] PVSyst: software package for the study, sizing, simulation and data analysis of complete PV systems ([www.pvsyst.com](http://www.pvsyst.com)).
- [12] Beaudin M, et al, "Energy storage for mitigating the variability of renewable electricity sources: An updated review", Energy for Sustainable Development (2010), doi:10.1016/j.esd.2010.09.007
- [13] Ioannis Hadjipaschalis, Andreas Poullikkas and Venizelos Efthimiou, "Overview of current and future energy storage technologies for electric power applications", Renewable and Sustainable Energy Reviews Volume 13, Issues 6-7, August-September 2009, Pages 1513-1522.
- [14] J.L. Bernal-Agustín, R. Dufo-López, "Simulation and optimization of stand-alone hybrid renewable energy systems", Renewable and Sustainable Energy Reviews 13 (2009) 2111–2118.