Stand-alone hybrid renewable energy systems (HRES)

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KU LEUVEN

PhD Thesis

Stand-alone Hybrid Renewable Energy Systems (HRES)

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Dedicatoria

Dedico esta tesis a mis padres.
Por su infinito amor, apoyo incondicional y motivación diaria incansable.

This thesis is dedicated to my parents.
For their infinite love, unconditional support and encouragement always.

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Again my thanks to everybody, whether mentioned here or present in my memories of those years, for the support and encouragement for the accomplishment of this PhD.

Abstract

Ending of Energy Poverty and achieving Sustainable Energy for All by 2030 are global challenges for humanity. 1.3 billion people without energy access and 2.8 billion people using unsustainable solid fuel for cooking and heating are global challenges for human and societal sustainable development. Nearly $1 trillion of investment is expected in the Sustainable Energy for All (SE4ALL) scenario to achieve universal energy access by 2030. Around 60% of investments will be in isolated off-grid and mini-grid systems with the relevant goal of duplicating the renewable energy sources in the energy mix.

Access to innovation trends in renewable energy off-grid would benefit future installations. This work brings to light research contributions in Hybrid Renewable Energy Systems (HRES) and related aspects that benefit these required investments in isolated off-grid and mini-grid systems. "Hybrid Renewable Energy Systems (HRES) consist of two or more energy sources, with at least one of them renewable, integrated with power control equipment and an optional storage system". HRES as defined previously can be found in the literature also under other terms such as: standalone hybrid energy (or power) system, off-grid, remote, islanded, hybrid system, hybrid energy (or power) system, micrograds, mini-grids or autonomous power systems, among others.

An overview on the thematic focus of research in Hybrid Renewable Energy Systems (HRES) in the last decade, period 2005 - 2015, is provided. This review covers multiple key aspects of HRES as: the main focus of the research (technical, economic, environmental, financial, etc.); the design of the system (type of load, energy sources, storage, availability of meteorology data, etc.); different optimization criteria and objective function; software and modelling tools; and the type of application and country among others. A methodology for searching, identifying and categorizing the innovations related to HRES is proposed. Applying this methodology during this PhD work resulted in a primary database with a categorized bibliography including nearly 400 entries.

Currently, system design is mainly technically driven by economic feasibility analysis focused on energy cost and return on investment. As for environmental aspects, the beneficial impacts of renewable energy are rarely considered as an economic value. Regarding decision-making tools, the most currently used optimization algorithms and software tools for the design of HRES is HOMER and a case study for understanding is proposed. Following the analysis of most popular and relevant criteria, an easy to use

guideline is proposed encouraging decision-making for more sustainable energy access. The access to affordable tools for decision-making integrating technical, economic and environmental aspects would ease the roll-out of HRES.

There are untapped research opportunities for HRES in multi-disciplinary thematic areas. The analysis of innovations regarding the system design for Hybrid Renewable Energy Systems (HRES) have identified potential for the research community aligned with the trends to integrate the value chain and foster innovative business models and sustainable energy markets. Those identified opportunity areas for future innovations would have many benefits like: multi-disciplinary approach to develop innovative business models and other enabling areas, and introducing the environmental benefits in the decision making while encouraging more investments.

After the analysis of those criteria from technical and economic, to environmental, the regulatory and policy aspects, an integrated value chain for HRES systems is defined. More research on viable business models and enabling regulatory and policy frameworks is needed. Sharing those findings and building on the primary database with more innovations will help to plot trends on renewable energy in off-grid power system as well as identify those untapped research opportunities and future potential innovations for the benefit of the whole value chain of stand-alone HRES.

After sharing innovations and providing methodologies and tools, facilitating networking among researchers has proven to be a powerful tool to tackle untapped research potential with multidisciplinary and international teams. For this reason I have created the website ElectrifyMe (www.electrifyme.org) in order to facilitate the research community to discover innovations and share projects. This initiative allows the research community to prepare for the future roll-out of HRES by: sharing innovations, encouraging knowledge transfer and facilitating networking. The role of the research community to transfer state-of-the-art technology and innovative business models will be essential to achieve the SE4ALL goals by 2030.

Knowledge, methodologies & tools are provided in this PhD work for more stand-alone hybrid renewable energy systems. After reviewing the latest innovations in HRES per thematic focus an integrated value chain for those systems has been proposed and multidisciplinary research opportunities have been identified. Identifying the need to include the environmental aspects in early stages of the decision-making process has lead to the development of an easy to use guideline integrating most relevant criteria for the design of stand-alone renewable power systems. Finally, the research opportunities identified and the untapped potential of transferring the latest innovations have resulted in the creation of the website ElectrifyMe (www.electrifyme.org) to enable valuable international networking contacts among researchers and encouraging multi-disciplinary research. "Knowledge, methodologies & tools" are powerful contributions by the research community and innovators to foster more sustainable energy for all.

Resum

El fi de la pobresa energètica i l'accés a energia sostenible per a tothom l'any 2030 és un repte universal. 1,3 mil milions de persones sense accés a l'energia i 2,8 mil milions de persones que utilitzen combustible sòlid insostenible per cuinar i escalfar són desafiaments globals per al desenvolupament humà i social sostenible. S'espera una inversió aproximada de $1 trilió en sistemes energètics sostenibles per aconseguir l'accés universal a l'energia en 2030, iniciativa de les Nacions Unides coneguda con Sustainable Energy for All (SE4ALL). Al voltant del 60% d'aquestes inversions seràn en sistemes off-grid i mini-grid, amb la corresponent meta dintre de la iniciativa SE4All de duplicar les fonts d'energia renovables en el mix energètic.

L'accés a les tendències d'innovació en energia renovable off-grid beneficiarà futures instal·lacions. Aquest treball posa de manifest les contribucions dels últims anys a la investigació en sistemes híbrids d'energia renovables (coneguts com HRES amb les seves sigles en anglès) i aspectes relacionats que es beneficiarien aquestes inversions per instal.lacions off-grid i mini-grid. Els "Hybrid Renewable Energy Systems" (HRES) consisteixen de dues o més fonts d'energia, amb el almenys una d'elles renovable, integrades amb un equip de control i un sistema d'emmagatzematge opcional". Els HRES com els proposo a la definició anterior es pot trobar en la literatura també sota altres termes com ara: sistema d´energia (o potència) independent híbrida, off-grid, sistema híbrid remot, en illa, sistema d´energia (o potència) híbrida, microxarxes, mini-xarxes i sistemes d'alimentació autònoms, entre d'altres.

En aquesta tesis es facilita una visió general sobre els àmbits temàtics de la recerca en Hybrid Renewable Energy Systems (HRES) en la darrera dècada, període 2005-2015. Aquesta revisió es refereix a diversos aspectes clau dels HRES com: el focus principal de la investigació (tècnics, econòmics, ambientals, financers, etc.); el disseny del sistema (tipus de càrrega, fonts d'energia, l'emmagatzematge, la disponibilitat de dades de meteorologia, etc.); diferents criteris d'optimització i funció objectiu; programari de modelatge i eines; i el tipus d'aplicació i el país, entre d'altres. En aquest treball es proposa una metodologia per buscar, identificar i categoritzar les innovacions relacionades amb els HRES. L'aplicació d'aquesta metodologia durant aquest treball de doctorat proporciona una base de dades primària amb una bibliografia classificada incloent prop de 400 registres.

Actualment el disseny dels sistemes HRES incorporen criteris tècnics amb anàlisi de viabilitat econòmica sobre el cost de l'energia i el retorn de la inversió. Respecte als aspectes ambientals, els efectes beneficiosos de les energies renovables rarament s'introdueixen com un valor econòmic. Pel que

fa a les eines de presa de decisions, el software d'optimització més utilitzat en l'actualitat per al disseny de HRES és HOMER. En aquest treball de doctorat es proposa un estudi de cas inicial per a la comprensió dels criteris de disseny utilitzant HOMER. Després de l'anàlisi de la majoria dels valors més habituals i rellevants, es proposa una senzilla guia per la presa de decisions per introduir fonts d'energia renovables i dissenyar sistemes més sostenible. L'accés a eines assequibles integrant aspectes tècnics, econòmics i ambientals facilitaria la posada en marxa de HRES més sostenibles.

Hi ha oportunitats de recerca sense explotar per HRES en àrees temàtiques multi-disciplinars. L'anàlisi de les innovacions en relació amb el disseny dels sistemes HRES han identificat el potencial per a la comunitat d'investigació en línia amb les tendències d'integració de la cadena de valor i fomentant models de negoci innovadors i mercats d'energia més sostenibles. Aquestes àrees d'oportunitat identificades per a futures innovacions podem aporten beneficis com: un enfocament multidisciplinari per desenvolupar models de negoci innovadors, i la introducció dels beneficis ambientals en la presa de decisions, tot encoratjant més inversions.

Després de l'anàlisi dels diferents àmbits temàtics que van des dels tècnics i econòmics, als aspectes ambientals, de regulació i polítics, es defineix una cadena de valor integral per a sistemes HRES. Més investigació sobre models de negoci viables i marcs reguladors i polítics afavoridors es necessària. Compartir aquestes troballes i construir sobre la base de dades primària amb més innovacions facilitarà a totes les parts interessades compartir els avenços en matèria d'energia renovable off-grid. Això també permetrà la identificació d'oportunitats de recerca sense explotar i innovacions potencials futures per al benefici de tota la cadena de valor.

Després de compartir innovacions i proporcionar metodologies i eines, facilitar la creació de xarxes entre els investigadors ha demostrat ser una poderosa eina per promoure recerca sense explotar amb equips multidisciplinaris i internacionals. Per aquest motiu, he creat la pàgina web ElectrifyMe (www.electrifyme.org) per facilitar a la comunitat científica de descobrir les innovacions i compartir projectes. Aquesta iniciativa té com a objectiu promoure el futur desplegament de HRES a través de: compartir innovacions, afavorir la transferència de coneixements i facilitar la creació de noves col.laboracions. El paper de la comunitat científica per transferir tecnologia d'última generació i models de negoci innovadors serà essencial per assolir els objectius del SE4ALL al 2030.

Coneixements, metodologies i eines & es proporcionen en aquest treball de doctorat per afavorir la creació de valor als sistemes aïllats híbrids renovables (stand-alone HRES). Després d'analitzar les darreres innovacions en la introducció de renovables en sistemes aïllats amb diferents enfocs temàtics, s'han identificat oportunitats de recerca multi-disciplinars i s'ha proposat una cadena de valor integrada per aquests sistemes. La identificació de la necessitat d'incloure els aspectes ambientals en les primeres etapes de la presa de decisions ha portat a proposar una guia fàcil per utilitzar la integració de criteris més rellevants per al disseny de sistemes d'energia renovables independents. Finalment, les oportunitats de recerca identificades i el potencial sense explotar tenen com a resultat la creació de la pàgina web ElectrifyMe (www.electrifyme.org) per promoure contactes i col.laboracions de xarxes internacionals d'investigadors i el foment de la investigació multidisciplinar. "El coneixement, les metodologies i les eines & són poderoses eines de la comunitat científica per aconseguir un accés sostenible a l'energia per tothom.

Thesis Outline

This PhD presents the research conducted on the design criteria of stand-alone hybrid renewable energy systems (HRES) for sustainable energy development. The Sustainable Energy for All (SE4All) scenario to eradicate world energy poverty and the scope of this research are detailed in **Chapter 1**. The sensitivity of the stand-alone HRES system's design to different criteria eg. economic, technical and environmental, is introduced via a case study in **Chapter 2**. The core of the research focuses on the design criteria for more sustainable energy systems beyond economic optimization (**Chapter 3** and **Chapter 4**) and the value chain for more integration of renewable off-grid over optimal system design (**Chapter 5**).

Chapter 3 describes a methodology for searching, identifying and categorizing the innovations related to a multiple criteria design, beyond most popular economic factors, for off-grid renewable energy systems. At the end of this chapter an overview of the most predominant energy sources, different hybrid configurations and the most popular storage systems for Hybrid Renewable Energy Systems (HRES) in the decade 2005 - 2015 is provided.

Chapter 4 starts with an analysis of the latest innovations system design criteria. Following this, the most currently used optimization algorithms and software tools for the design and decision-making of HRES is introduced. Finally, an easy guideline is proposed introducing the most relevant criteria.

Chapter 5 proposes a value chain for more integration of renewable off-grid over optimal system design. An overview of the thematic focus of research in the decade 2005 - 2015 is provided. This thematic focus analysis points out the needs and opportunities for the research community, business and public bodies to include, among others, more regulatory and political aspects involved in the integration of hybrid renewable energy systems off-grid. After sharing innovations and providing tools, facilitating networking has proven to be a powerful tool to tackle untapped potential with multidisciplinary and international teams. For this reason, I have created the website www.electrifyme.org to facilitate the research community to discover and share innovations that are having an impact in real-life installation in different countries. This website allows the research community to prepare for the future roll-out of renewables off-grid.

Chapter 6 goes on to conclusions. Identifying the need to include the environmental aspects in early stages of the decision-making process has lead to the development of an easy guideline integrating the most relevant criteria for the design of stand-alone renewable power systems. After reviewing the latest innovations in HRES per thematic focus an integrated value chain for those systems has been proposed and multidisciplinary research opportunities have been suggested. Finally, the research opportunities identified and the untapped potential of transferring latest innovations have resulted in the creation of the website www.electrifyme.org to empower valuable international networking contacts among researchers. "Information, tools & networking" are called to empower the research community and innovators to achieve sustainable energy for all by 2030.

Abbreviations

List of abbreviations

Abbrev.	Description
AC/DC	Alternating current (AC) and direct current (DC)
ACS	Annualized Cost of the System
BIPV/T	building integrated PV/T
CITCEA	Technology transfer centre of UPC University
CO2	Carbon dioxide
CHP	Combined heat and power
COE	Cost of Energy
DER	Distributed Energy Resources
DG	Distributed Generation
DR	Demand Response
EE	Excess of Electricity
EENS	Expected Energy not Supplied
EMS	Energy Management System
EoE	Excess of Electricity
EIT	European Institute of Innovation and Technology
FC	Fuel cell
GIS	Geographic Information System
GPV	DF Electric company PV panel
GW	Gigawatts
HEP	Hydroelectric power plant
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid Renewable Energy Sources
ICT	Information and Communication Technology
IEA	International Energy Agency
IOD	Integrated Optimal Design
KIC	Knowledge and Innovation Community
kW	Kilowatt
kWh	Kilowatt-hour(s)
kWp	Kilowatt peak

Abbrev.	Description
LA	Level of Autonomy
LCA	Life Cycle Assessment
LCE	Levelized Cost of Energy
LCOE	Levelized Cost of Energy
LEM	Load Energy Market
LOLH	Loss of load hour
LOLP	Loss of load probability
LPSP	Loss of Power Supply Probability
mWind	Micro wind turbine
MW	Megawatts
NGO	Non-governmental organization
NPC	Net Present Cost
NPV	Net Present Value
NZEB	Net Zero Energy Building
PHS	Pumped Hydro Storage
PMS	Power management strategy
PV	Photovoltaics
PVsyst	Photovoltaic software
PV/T	Photovoltaic-thermal collectors
PEMFC	Polymer electrolyte membrane (PEM) fuel cells
RF	Renewable Fraction
RES	Renewable Energy Sources
RETScreen	Clean Energy Project Analysis Software
SE4ALL	Sustainable Energy for All
SOC	State of charge of the batteries
Solar	Solar Thermal
TCO	Total cost of ownership
UN	United Nations
UNESCO	UN Educational, Scientific and Cultural Organization
UPS	Interruptible power supply
USD	United States Dollar
WT	Wind turbine
UPC	Universitat PolitÃ¨cnica de Catalunya
URFC	Unitized regenerative fuel cell
USA	United States of America

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Chapter 1

Introduction

1.1 Potential of introducing renewable energy resources off-grid

The potential of introducing renewable energy resources off-grid via stand-alone renewable hybrid energy systems is impressive. Nowadays, with price variations of fossil fuels [1] shown in figure 1.1, the increasing need to cut CO2 emissions and better performance and affordability of renewable technologies, all communities or facilities that were formerly isolated from the grid could be powered at a reasonable cost level with these systems.

It is currently estimated that approximately 1,3 billion people (almost one out of 7 people in the world) do not have access to electric power. Lack of coverage by a conventional power grid is explained by many factors: distances involved in meeting the demand of low-income consumers, natural barriers, lack of interest of energy utilities, among others. The scarcity of energy/electric power in isolated communities or in developing countries is a barrier to economic and social development.

Many of the current stand-alone power systems are diesel generators that present issues, such as: fluctuations and uncertainties in variable fuel price, CO2 emissions, acquisition cost of diesel generators, operation and maintenance costs, inefficiency, advanced age of the facilities, diesel transport, lack of subsidies, penalties for CO2 emissions, etc.

Hybrid renewable power systems are being considered more and more and will grow and take advantages of the positive benefits (free of charge renewable resource availability, CO2 emissions reductions, subsidies, etc.) and deal with the inconveniences (variability of renewable resources availability, cost acquisition, etc.) through the optimization of the design and the control of the systems.

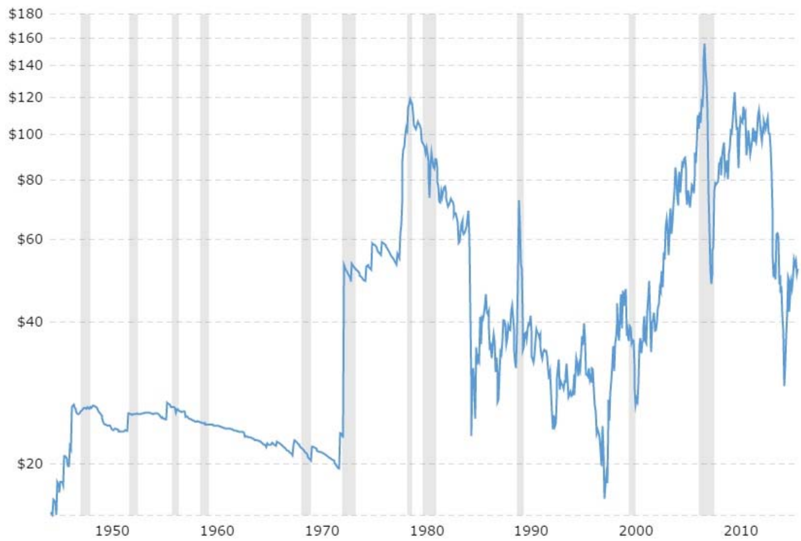

Figure 1.1: Crude Oil Prices - 70 Year Historical Chart, source: [1]

1.2 Access to Sustainable Energy

Energy access is vital for poverty eradication and sustainable development[2]. One out of five people in the world lack access to electricity, 1.3 billion worldwide [3]. While 2.8 billion people still use unsustainable solid fuels for cooking and heating. Most of them are living in rural communities in sub-Saharan Africa countries and developing countries in Asia [4]. 2014-2024 has been declared the United Nations Decade of Sustainable Energy for All.

Sustainable approach to energy access and use The main change drivers in the access to sustainable energy at world level [5] identified by the International Energy Agency (IEA) in 2011 are:

- 1.3 billion people worldwide lack access to electricity, where 95% of this energy poverty is in sub-Saharan Africa or developing Asia and 84% of this population lives in rural areas.
- World energy demand has increased dramatically, with a 39% growth from 1990 to 2008. This increase is mainly driven by developing countries: Middle East 170%, China 146%, India 91%, Africa 70% or Latin

America 66%.

- $1 trillion is the estimated cumulative investment in cost infrastructure to cope with the "Energy for all" case. Where the grid is not available, or when there is a need for reinforcement of the existing grids, the introduction of hybrid systems in stand-alone mode provides a cost-effective solution.

The SE4ALL scenario The goal of the SE4ALL initiative is to "ensure universal access to modern energy" and to "double the share of renewable energy in the global energy mix". The International Energy Agency (IEA) estimated in 2011 nearly $1 trillion of investment is required to achieve universal access to energy by 2030. 60% of these investments, $20 billion annually, are expected to be in isolated off-grid and mini-grid solutions [5].

1.3 What are Hybrid Renewable Energy Systems (HRES)?

Hybrid Renewable Energy Systems (HRES) can be found under different terms and definitions and also considered as part of the general concept of Distributed Energy Resources (DER) or Distributed Generation (DG). The are many terms and concepts that enable to find the research breakthroughs related to HRES the within literature.

1.3.1 Definition and terms

More than 12 terms can be found in literature to refer to innovations in HRES. A total of 172 articles have been identified defining HRES under different terminology. Most of them refer to the hybridization of conventional energy systems introducing renewable energy sources as alternatives to a grid connection. As can be observed in figure 1.2, the terminology goes from the most general terms of Renewable Energy Sources (RES) to the most technical.

I propose the following general definition for HRES:

"Hybrid Renewable Energy Systems (HRES) consist of two or more energy sources, with at least one of them renewable and integrated with power control equipment and an optional storage system." HRES as defined above can be found in the literature also under other terms such

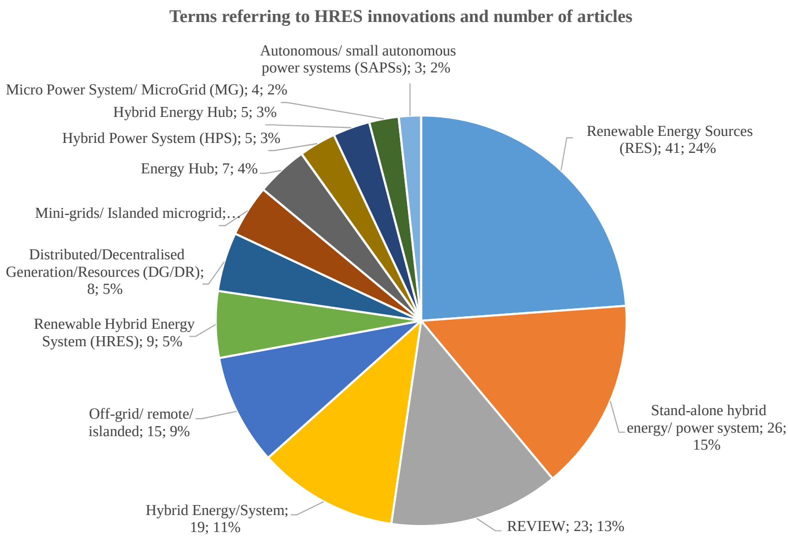

Figure 1.2: Terms for HRES (total 172 publications, period 2005-2015)

Figure 1.3: Own definition for HRES: "Two or more energy sources, with at least one of them renewable and integrated with power control equipment and an optional storage system."

as: stand-alone hybrid energy (or power) system, off-grid, remote, islanded, hybrid system, hybrid energy (or power) system, microgrids, mini-grids or autonomous power systems. The specific reference for each of the terms is detailed in the following sections and summarized in table 1.1. Also relevant literature for those systems can be found under the terms of Distributed Energy Resources (DER) or Decentralized Generation (DG), among others as described next.

Stand-alone Hybrid Renewable Energy (or Power) System

Stand-alone Hybrid Renewable Energy (or Power) Systems are found as the integration of several generation systems, with at least one renewable (photovoltaic (PV), wind, diesel, hydrogen, fuel cell), and optional storage system (battery, fuel cell).

These hybridization by combining several generation systems and optional storage are found in very different configurations as follows:

- PV/battery [8] [9] [10] [56]
- PV/microturbine [34]
- PV/wind/Hydrogen [18]
- PV/Wind/fuel cell [21]
- PV/Hydrogen/battery [31] [32]
- PV/micro-Wind/URFC/battery [33]
- PV/diesel/battery [35] [36]
- Wind/PV/battery [37] [38] [39]
- Wind/turbine/storage [46]
- Wind/diesel/battery [49] [50]
- Wind/PV/diesel/battery [43] [44]
- Fuel cell/PV/battery [52]

Without mentioning the ”Stand-alone” capability or limitation by design,the following system configurations are studied in the literature as Hybrid Renewable Energy (or Power) Systems:

Terms and definitions versus Technologies and Renewable Energy Sources	3.1.1 Stand-alone Hybrid Renewable Energy Systems	3.1.1 without mentioning Stand-alone	3.1.2 Off-grid/ remote or islanded	3.1.3 Hybrid Energy (or Power) System
PV		[6]	[7]	
Battery/PV	[8][9][10]		[11]	
Grid/Battery/PV			[12][13]	
Wind/PV		[14][15]		[16][17]
Hydrogen/Wind/PV	[18]	[19]		[20]
Fuel cell/Wind/PV	[21]			
Battery/Wind/PV				[22][23][24]
Diesel/Battery/Wind/PV		[25]		
Grid/Diesel/Wind/PV				[26]
Hydro/PV				[27][28][29]
Battery/Biodiesel/Hydro/PV			[30]	
Battery/Hydrogen/PV	[31][32]			
Battery/URFC/mWind/PV	[33]			
Microturbine/PV	[34]			
Battery/Diesel/PV	[35][36]			
Battery/PV/Wind	[37][38][39]			
Water pump/PV/Wind				[40]
Battery/Diesel/FC/PV/Wind				[41]
Diesel/PV/Wind				[42]
Battery/Diesel/PV/Wind	[43][44]			
Hydro/Wind			[45]	
Storage/Turbine/Wind	[46]			
Wind/Gas plant/Hydro				[47]
Hydro/Diesel/Wind				[48]
Battery/Diesel/Wind	[49][50]			
Wind/Solar/Hydro			[51]	
Battery/PV/Fuelcell	[52]			
Wind/Diesel				[53]
Wind/Solar/Hydro/Diesel			[54][55]	

Table 1.1: Summary of terms and definitions versus technologies and renewable energy sources

- PV [6]
- PV/Wind [14] [15]
- PV/Wind/Hydrogen [19]
- PV/Wind/Diesel/battery [25]

Off-grid, remote or islanded

Off-grid are found synonymous with Stand-alone hybrid energy/power systems as the integration of several generation systems, with at least one renewable source of energy (photovoltaic (PV), wind, diesel, hydrogen, fuel cell), and optional storage system (battery, fuel cell). When referring to Off-grid systems the location is usually without access to a main electricity grid, so generally they are placed in remote locations or rural areas. In the case an off-grid system might be connected to the grid, then the functionality of working disconnected and independently from the grid is known as stand-alone or islanded mode. It has been identified a preference of usage of off-grid for a more broad audience, while the usage of stand-alone is more restricted within the research community.

The configuration of Off-grid systems might be as the following ones:

- Diesel/Hydro/Solar/Wind [54] [55]
- Hydro/Solar/Wind [51]
- PV/Hydro/Biodiesel/battery [30]
- PV/battery/grid [12] [13]
- PV [7]
- PV/battery [11]
- Wind/hydro [45]

Hybrid Energy (or Power) System

Hybrid Energy systems are a more general approach and the systems under this term in the literature could also be considered as "stand-alone" or "off-grid" systems. Those systems are small energy set-ups that can not be considered as operating networks. A definition for Hybrid Power Systems, according to [57] are combinations of two or more energy conversion devices (including storage) or two or more fuels for the same device that when integrated can improve the system performance or overcome limitations that may be inherent in either. Following this definition, the systems found under the terms of the previous subsections could be considered also as Hybrid Energy (or Power) Systems.

Examples of configuration for Hybrid Energy (or Power) systems in the literature are the following ones:

- PV/Wind [16] [17]
- PV/Hydro [27] [28] [29]
- PV/Wind/battery [22] [23] [24] [58] [59]
- PV/Wind/Hydrogen [20]
- PV/Wind/Diesel/grid [26]
- Wind/PV/water pump [40]
- Wind/PV/fuelcell/diesel/battery [41]
- Wind/Gas plant/Hydro [47]
- Wind/PV/Diesel [42]
- Wind/Diesel/Hydro [48]
- Diesel/Wind [53]

Other terms: Microgrid, mini-grid, autonomous power system or Energy Hubs

Other terms as islanded Microgrid [60] [61], mini-grid [62] or autonomous power system [63] appear to be studying systems which could be included within the definition of HRES. Hub or Energy Hub, or even Hybrid Energy Hub, are terms more frequently used when electricity and heating are integrated in a multi-source and multi-product energy system. These terms are found in literature [64] [65] [66] [67] [68] and the systems studied in those references still could also be considered under the definitions in the previous subsections. A different definition by [69] about Energy hubs defines them as an interface between energy producers, consumers and the transportation infrastructure. This work is not specifically related to the recently developed term of ”energy cell’.

Distributed Energy Resources (DER) and Decentralized Generation (DG)

Relevant research of the interest for HRES systems can also be found under the terms of Distributed Energy Resources (DER) or Decentralized Generation (DG) or even within the integration of Renewable Energy Sources (RES).

Examples of research under these terms that contributes to the potential introduction of HRES systems with different focus are:

- worldwide scientific production 1979-2009 [70] and mapping of knowledge in developing countries [71]
- renewable energy technologies as solar [72] or bioenergy [73],
- introduction of RES in developing countries [74] and for decentralized electrification [75]
- RES in countries as China [76] , Pakistan [77], Ethiopia [78] [79], in Africa [80]
- islands [81] [82] [83] [84] [85]
- applications as soustainable tourism [86], residential [87] [68] and eco-cities in China [88], or
- storage for RES, via an European research project [89]

1.4 The research questions

The research focus of this work is:

How to enhance the research of stand-alone Hybrid Renewable Power Systems:

- beyond economic optimization of the system, identifying other relevant criteria and research opportunities,
- and beyond system design, providing a more integrated approach that creates value for stakeholders,

for a more environmentally friendly and sustainable energy access for all.

In order to provide answers to the research question, the driving values for this PhD work are:

- Achieving sustainable and renewable energy for all.
- Acknowledging trends and disruptive innovations relevant for the energy sector.
- Facilitating access to innovation trends in off-grid installations.
- Encouraging research in untapped research opportunities in different thematic areas.
- Providing easy to use open decision-making tools integrating technical and economic with other relevant aspects.
- Enabling valuable networking contacts among researchers.

1.5 Summary of change drivers for more renewable energy off-grid

Ending of Energy Poverty and achieving Sustainable Energy for All by 2030 is paramount. 1.3 billion people without energy access and 2.8 billion people using unsustainable solid fuel for cooking and heating are global challenges for human and societal sustainable development.

Nearly $1 trillion of investment is expected in the Sustainable Energy for All (SE4ALL) scenario to achieve universal energy access by 2030. Around 60% of investments will be in isolated off-grid and mini-grid systems with the relevant goal of duplicating the renewable energy sources in the energy mix.

Access to innovation trends in off-grid installations with renewable energy would be enabling untapped research opportunities. This work brings to light research contributions in stand-alone Hybrid Renewable Energy Systems (HRES) and related aspects that benefit these required investments in isolated off-grid and mini-grid systems.

"Hybrid Renewable Energy Systems (HRES) consist of two or more energy sources, with at least one of them renewable and integrated with power control equipment and an optional storage system." HRES as I define here can be found in the literature also under many terms like: standalone hybrid energy (or power) system, off-grid, remote, islanded, hybrid system, hybrid energy (or power) system, microgrids, mini-grids and autonomous power systems, among others.

Chapter 2

Understanding design criteria sensitivity for stand-alone HRES

There is definitely huge potential growth for renewable hybrid power systems in the years to come. This is mostly because, no single renewable energy can solve the global and individual energy need alone. The sun is available during the day and not at night. Wind is not permanent but intermittent. Therefore, the solution would be to combine different renewable energy technologies in hybrid systems: PV plus Wind, PV plus Diesel, PV plus Wind, etc.

2.1 Overview of multiple design criteria

This chapter aims to bring some highlights to the different key factors that determine the design of a stand-alone renewable hybrid power system. A case study is proposed in order to analyse the sensitivity of the system design to multiple factors depending on the objective function, e.g. economic aspects (Net Present Cost (NPC), Cost Of Energy (COE), etc.), technical variables (Rate of the Devices, State of Charge of the Batteries (SOC), Excess of Electricity (EE), etc.) or environmental factors (Renewable Fraction, CO2 emissions, site conditions, etc.).

To understand how these different key criteria influence the defined objective function and the impact on the system design, is a first step for further research on methodology for system design with higher performance.

2.2 Four main perspectives to be integrated in the system design

The main objective of this chapter is to understand how different key factors influence the defined objective function within the design of hybrid renewable power systems.

In order to design a stand-alone renewable hybrid power system there are four main perspectives to be considered: the demand/load characterization, the potential of renewable and conventional energy generation, the restrictions of the system and the variables to be optimized (objective function).

- To describe the load/demand side it is necessary to estimate the load, its variability through time (hours, day/night, month of the year), if there are critical loads or not and the reliability that the system require, among other aspects.

- The potential of renewable resources can be estimated with statistical data taking into account the localization, the weather conditions and other environmental variables. 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 is a wide range of aspects to be considered: the space of the facilities (potential limitation of renewable technologies), the stability conditions of interruptions (some loads can be disconnected or not if they are not considered 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 battery requirements and eventually redundancy systems to guarantee the isolated function mode.

- The main optimization principles, considered in the objective function might be as different 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, unmeet load, etc.

  Furthermore, the objective function might include not only economic aspects (Net Present Cost (NPC), Cost Of Energy (COE), Interest Rate, etc.), but also technical variables (Supply reliability, Rate of the charge of the equipment, State of Charge of the batteries (SOC), Excess of Electricity (EoE), Grid connection requirements if available, etc.) and environmental factors (Renewable Fraction (RF), CO2 emissions, site conditions, etc.), among others not so studied related to the legal framework and the subsidies/penalties associated with the generation technologies and differences among countries.

Several of these key factors are not static through time and in order to assure the optimal design of the system, different scenarios must be considered.

In order to get a basic understanding how these different factors contribute to the design of an optimal system, a case study has been proposed based on different scenarios for a stand-alone PV/Wind/Diesel/Battery system for a Telecommunication Centre in Spain. To construct the different scenarios at using freeware solutions, mainly HOMER, which uses the NPC (Net Present Cost) to optimize the system design.

2.3 Case study

The proposed case study aims to facilitate the definition of several scenarios for a stand-alone PV/Wind/Diesel/Battery system for a Telecommunication Centre in Spain. The reasons for choosing this case study are: it integrates at least two renewable energy sources (wind and solar, both being the most predominant) to hybridize a fuel powered system (Diesel generator) including storage (battery), for a critical load (Telecommunication centre) in a location with renewable source availability (higher for sun than for wind) so the sensitivity analysis provide relevant scenarios.

To construct these different scenarios the HOMER energy modelling software [90] is used. This software uses the Net Present Cost (NPC) to optimize the system design in each scenario.

The software HOMER Hybrid Optimization of Multiple Energy Resources (HOMER) model was developed by the National Renewable Energy Lab, a division of the U.S. Department of Energy. This microgrid software navigates the complexities of building cost effective and reliable microgrids that combine traditionally generated and renewable power, storage, and load management.

The energy model and the inputs are detailed in Apendix A.

2.3.1 Economic analysis

The cost analysis evaluates the incremental cost of the renewable system, by components in figure 2.1 and by cost type in figure 2.2. The financial analysis indicates whether the project is financially attractive or not in terms of cash flow, taxation, incentives and emissions reductions benefits (figure 2.3.

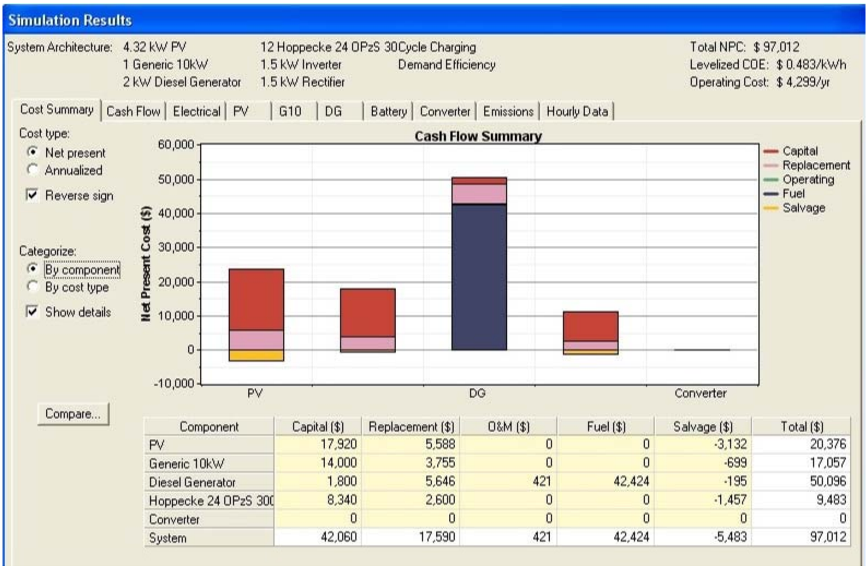

Figure 2.1: Cost analysis by component

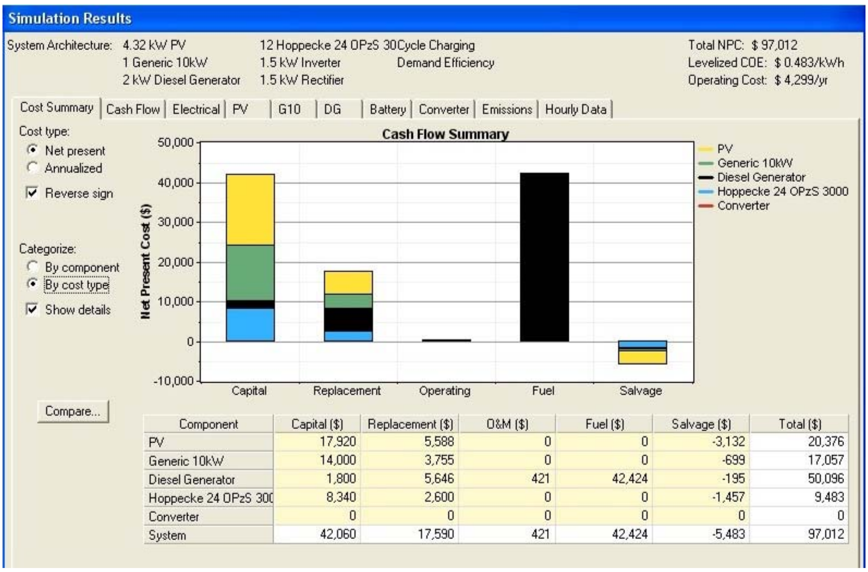

Figure 2.2: Cost analysis by type

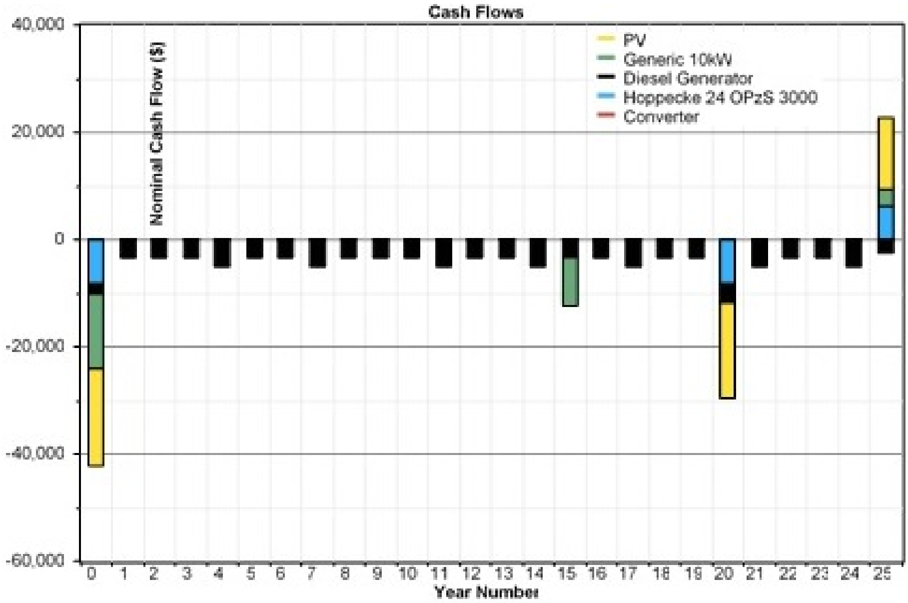

Figure 2.3: Financial analysis

2.3.2 Technical system analysis

Power output hourly data

The hourly data analysis of the HOMER software allows analysis of detailed simulation results in a variety of ways.

Figure 2.4 displays through hourly simulation data, for a stand-alone PV/Wind/Diesel/Battery system, the power generated by the different resources (conventional and renewable) and the influence of availability of wind resource through these variables: - Power output (kW) for the Wind turbine, PV system and diesel generator; - Wind speed (m/s).

Some of system characteristics that can be seen is that from 7 a.m. to 9 p.m. (14 hours) the diesel generator (with the support of the battery system) is the main source of power. Within this interval, corresponding to night time on the 10th of January, the output of the renewable part of the system is insufficient. It is also possible to check the operation of the battery bank through the next plot that displays hourly simulation data for the 10th of January, the variation of: - Power input (kW) at the AC primary load; - Battery state of charge (%).

The battery remains between a minimum of 75% and nearly full charge

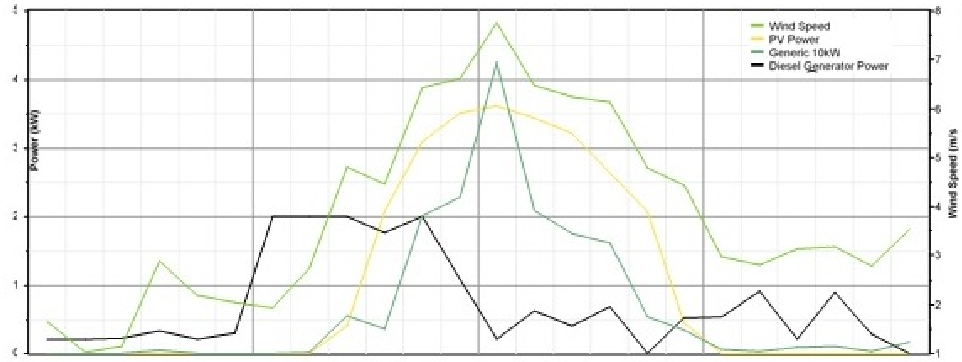

Figure 2.4: Power output (kW) PV/Wind/Diesel system and wind speed

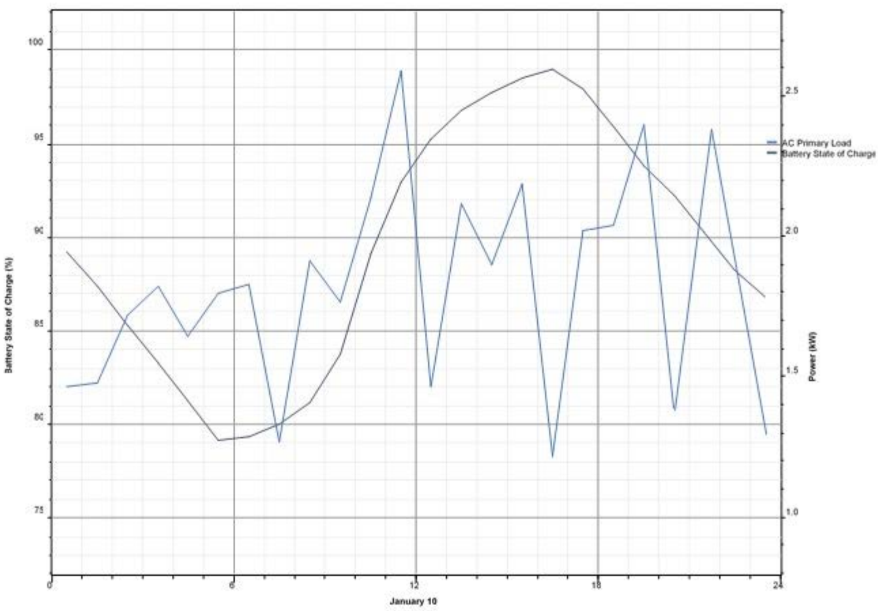

Figure 2.5: Power input (kW) and battery state of charge (%)

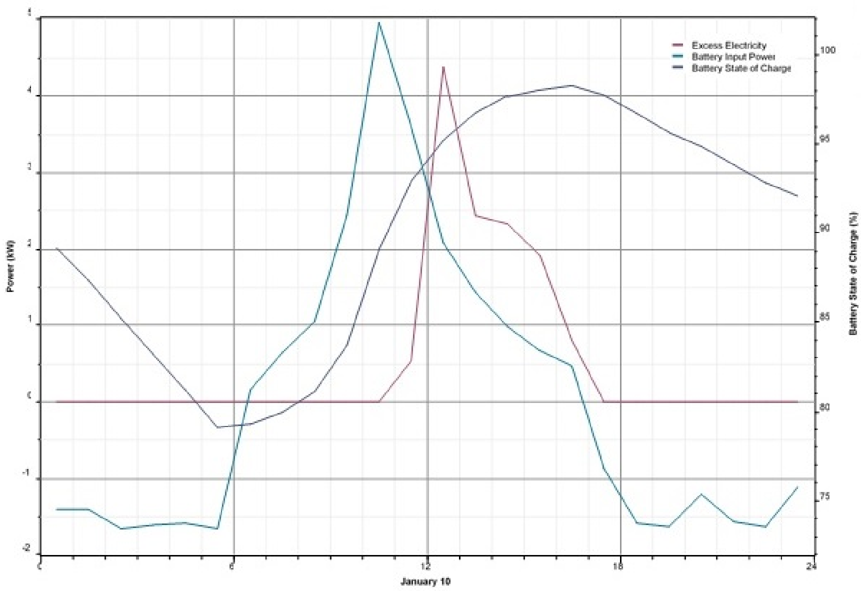

Figure 2.6: Battery input power (kW) and excess electricity to the total load (kW)

capacity for the whole day. Figure 2.5 shows that for the first half of the day the battery bank is able to get charged by the generation equipment, but after midday the load increases and the storage system supports the generation system.

In order to check the operation of the storage system, see figure 2.6 displays through hourly simulation data, for the following variables: - Battery input power and excess electricity in kW; - Battery state of charge (%).

The battery bank system does not have the capacity to completely store all the power generated. From 11a.m. to 6p.m. we can see an excess of electricity. With a greater battery bank we would be able to storage more renewable energy and reduce the need of the diesel generator. Moreover, with a possibility of being connected to the grid any excess energy produced could be sold, depending on the corresponding legal framework.

Technical analysis

The electrical section of the HOMER software, see figure 2.7, reveals several variables for the analysed system depending on the scenario: generation mix of each energy production system; RES-based generation in the electricity

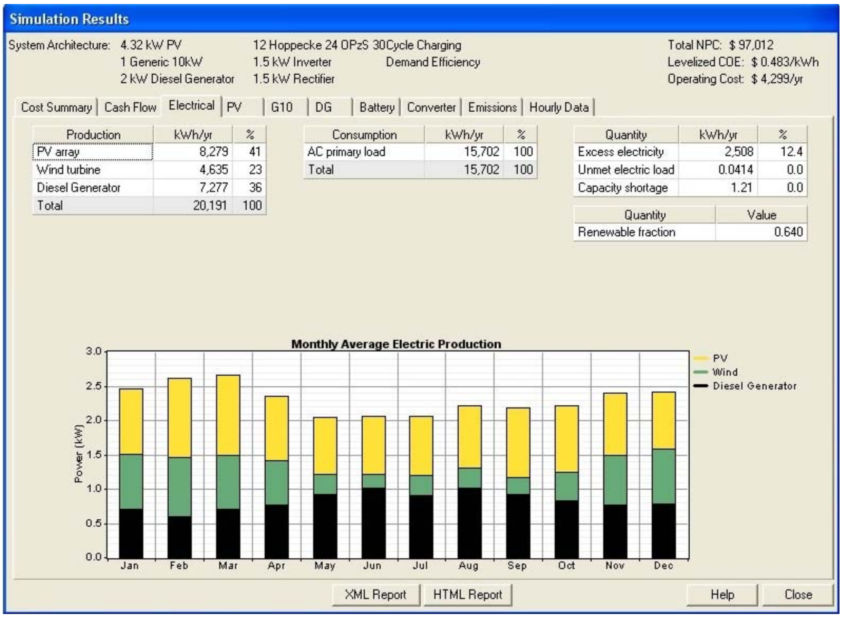

Figure 2.7: Electric production monthly average (kW)

available; monthly average of electric production; or excess electricity. In this case study, the unmet electric load (occurs when the electrical demand exceeds the supply) and the capacity shortage are fixed to zero, due to the critical characteristics of the load.

The PV tab, see figure 2.8, reveals the operation characteristics of a photovoltaic system: capacity factor, total production, hours of operation, levelized cost, etc.

The tab for the Wind turbine, see figure 2.9, reveals the operation conditions of a wind power system: capacity factor, total production, hours of operation, levelized cost, etc.

As for the Diesel generator, see figure 2.10, is showing the operation conditions of the fuel-based power system: capacity factor, total production, hours of operation, electrical production, mean electrical efficiency, etc.

The Battery, see 2.11, shows the configuration (number of batteries) and operation conditions of the electrical storage system: frequency histogram and monthly statistics of the State of Charge (%), etc.

Finally, for the Converter figure 2.12 shows the operation conditions of the electrical conversion system: capacity factor, hours of operation, etc.

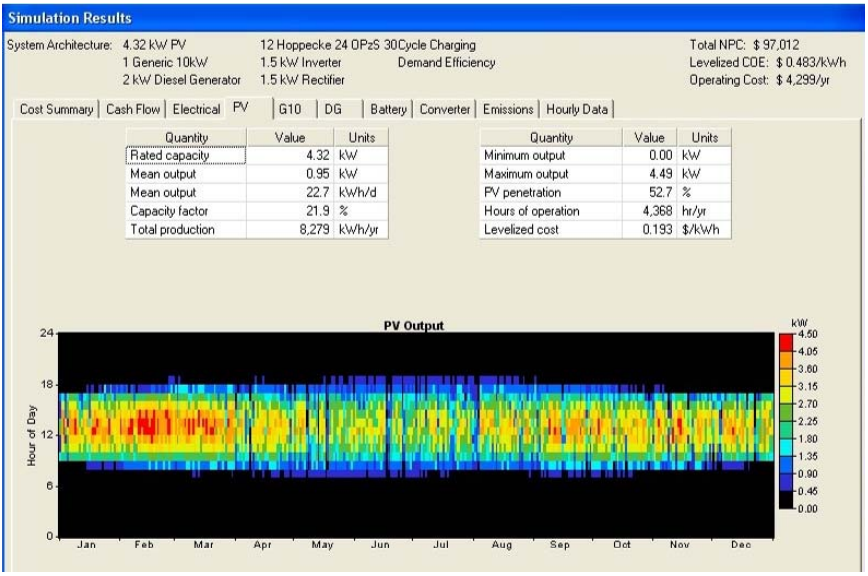

Figure 2.8: PV output (kW) of a 4.32 kW rated capacity PV system

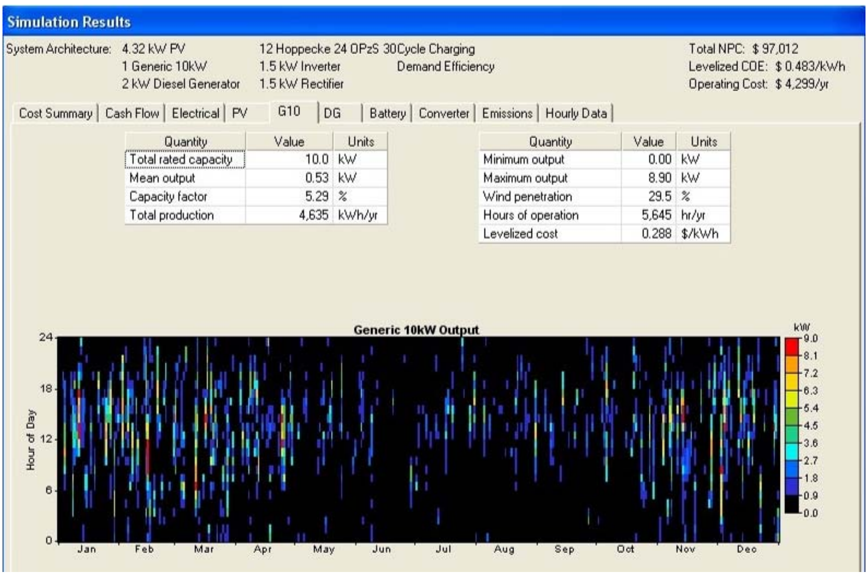

Figure 2.9: Wind output (kW)

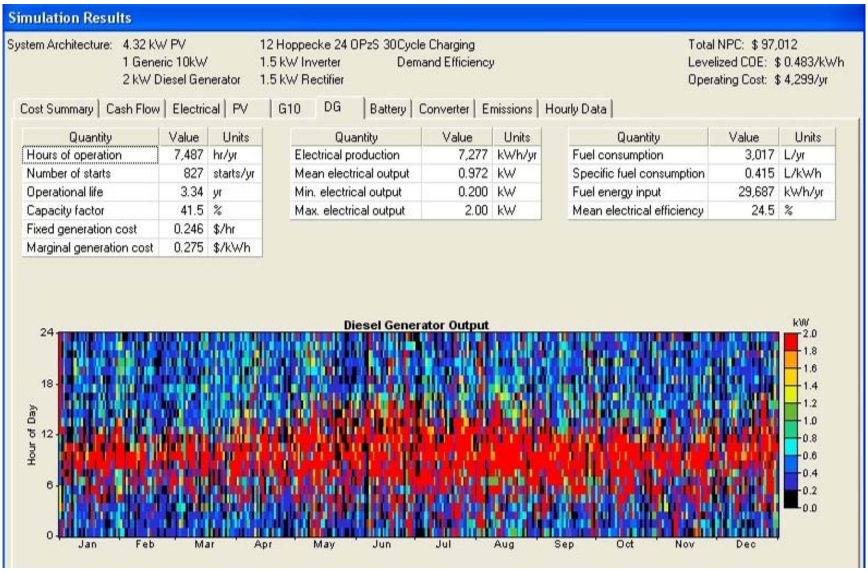

Figure 2.10: Diesel generator output (kW)

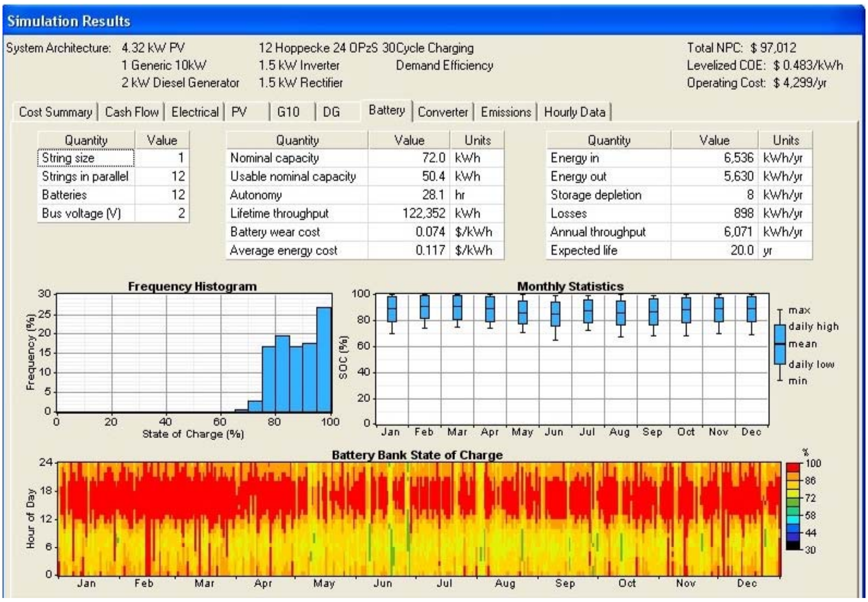

Figure 2.11: Battery configuration and operation conditions

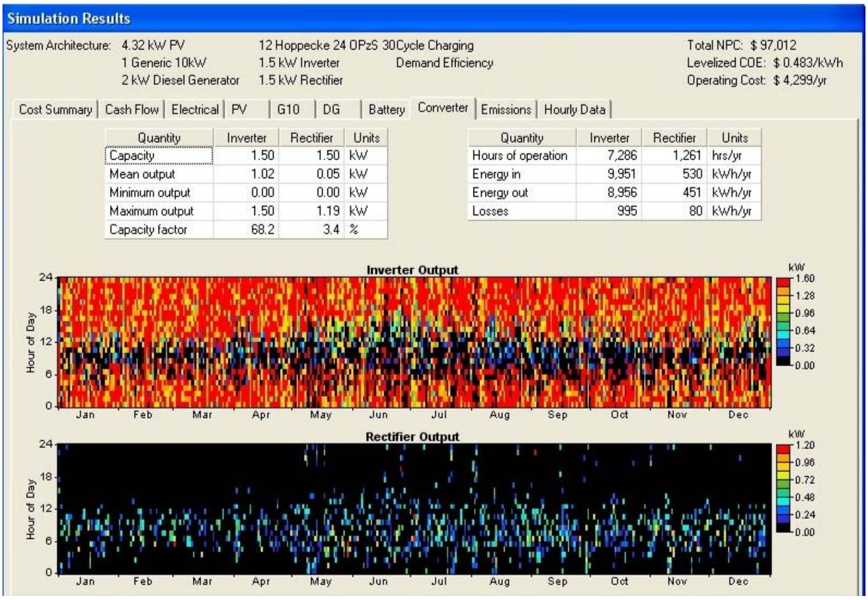

Figure 2.12: Converter operation conditions

2.3.3 Environmental analysis

For the emission analysis, the optional Green House analysis calculates the emissions reduction associated with the project, see figure 2.13. The calculi is done according to a standardized methodology developed by the United Nations Environmental project and the World Bank. This information about Emissions (kg/year) is provided for each of the analysed scenarios.

2.3.4 Sensitivity analysis to different design criteria

The sensitivity analysis aims to reveal how changes in inputs affect the design and feasibility of the system. In order to analyse the sensitivity of the system design to some of the mentioned factors different scenarios have been proposed depending on:

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

These two key factors have been chosen because for a critical load. Like the one analysed in the case study, the unpredictability of renewable resources is

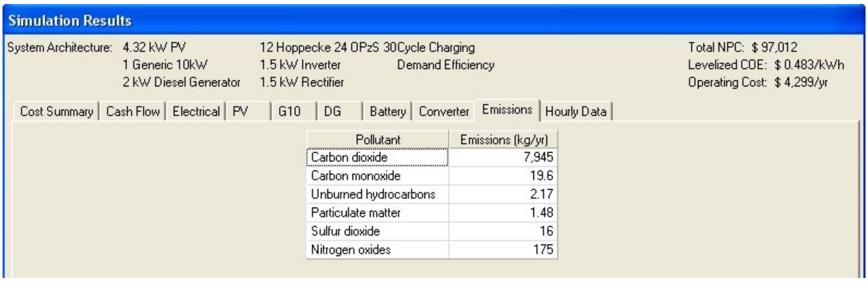

Figure 2.13: Environmental analysis

a constraint for the system design. As seen in the figure 2.14, the sensitivity variables that define the scenarios are:

- 0%, 20% and 40% of renewable fraction,
- 2,6 kWh/m2 and 5,09 kWh/m2 annual average of daily radiation.

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

- PV/Diesel/Battery
- Wind/Diesel/Battery
- Wind/PV/Diesel/Battery

In the following analysis a deeper look is taken into the sensitivity analysis for each variable within the defined scenarios.

System design sensitivity to Minimum Renewable Fraction (%)

The values for this sensitivity variable are: 0%, 20% and 40%. These are the three different scenarios to be studied:

- In the first case (0%), there are no constraints on the renewable percentage and to establish the system minimum NPC.
- In the second case (20%), systems are aligned with the European strategy that establishes a goal of 20% of the energy produced by renewable resources by 2020.
- In the third case (40%), we find systems similar to the Spanish energy case mix for renewables.

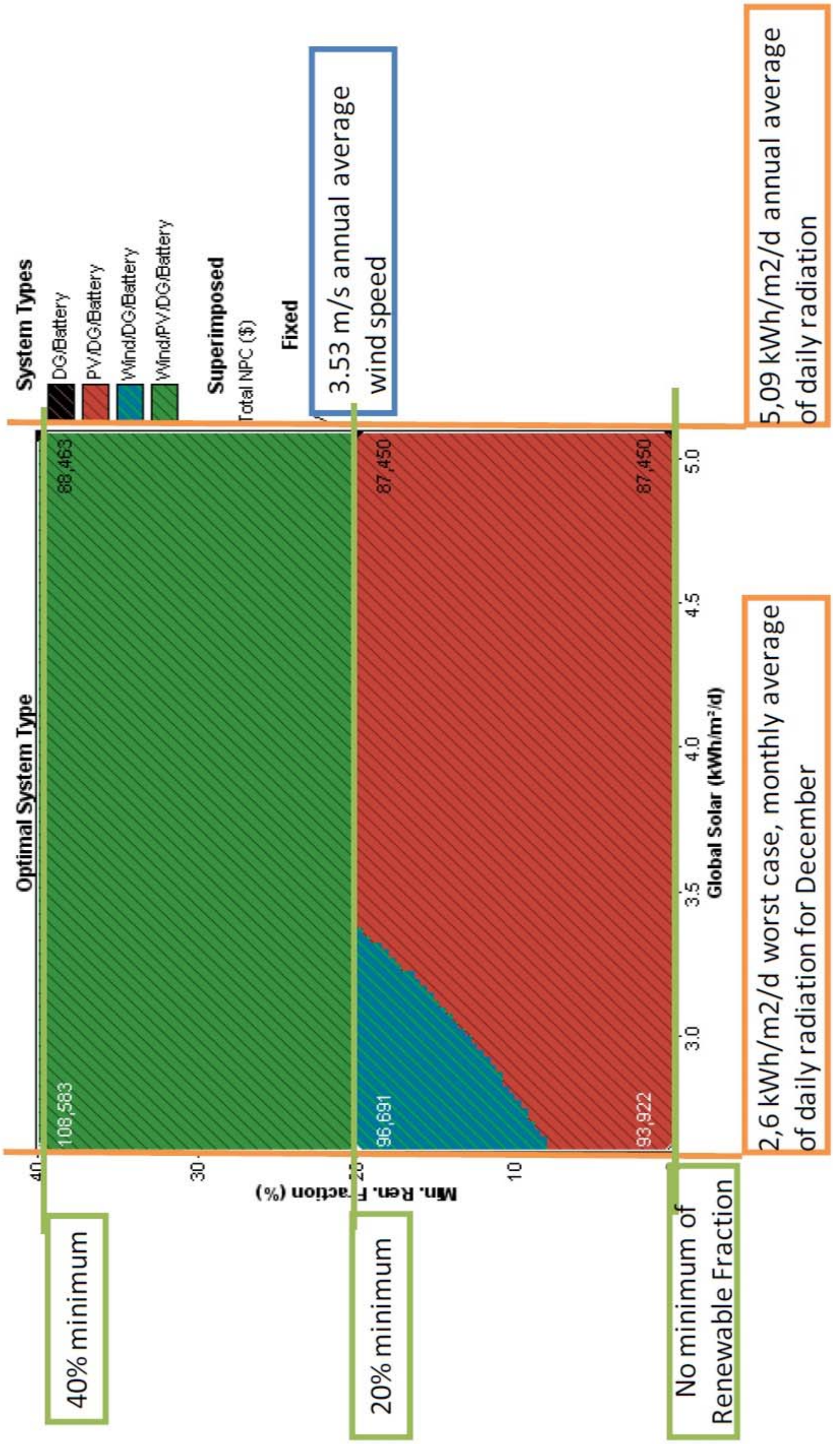

Figure 2.14: Optimal design space for the selected variable and given scenarios

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 5.09 Wind Speed (m/s) 3.53 Min. Ren. Fraction (%) 20

Double click on a system below for simulation results. Categorized Overall

PV (kW)	G10	DG (kW)	H3000	Conv. (kW)	Disp. Strgy	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
2.160		2	12	1.5	CC	Yes	$ 19,100	5,347	$ 87,450	0.436	0.25	4,288	7,277
0.135	1	2	12	1.5	CC	Yes	$ 24,700	5,626	$ 96,616	0.481	0.27	4,404	7,316
	1	2	12	1.5	CC	Yes	$ 24,140	5,675	$ 96,691	0.482	0.26	4,453	7,331
2.160		5		1.5	CC	Yes	$ 13,460	8,704	$ 124,722	0.621	0.25	6,588	8,682
0.135	1	5		1.5	CC	Yes	$ 19,060	8,975	$ 133,791	0.667	0.27	6,699	8,681
	1	5		1.5	CC	Yes	$ 18,500	9,022	$ 133,833	0.667	0.26	6,747	8,684

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 5.09 Wind Speed (m/s) 3.53 Min. Ren. Fraction (%) 20

Double click on a system below for simulation results. Categorized Overall

PV (kW)	G10	DG (kW)	H3000	Conv. (kW)	Disp. Strgy	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
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	1	5		1.5	CC	Yes	$ 18,500	9,022	$ 133,833	0.667	0.26	6,747	8,684

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 5.09 Wind Speed (m/s) 3.53 Min. Ren. Fraction (%) 40

Double click on a system below for simulation results. Categorized Overall

PV (kW)	G10	DG (kW)	H3000	Conv. (kW)	Disp. Strgy	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
4.320		2	12	1.5	CC	Yes	$ 28,060	4,725	$ 88,463	0.441	0.47	3,592	7,725
4.320	1	2	12	1.5	CC	Yes	$ 42,060	4,299	$ 97,012	0.483	0.64	3,017	7,487
4.320		5		1.5	CC	Yes	$ 22,420	8,329	$ 128,892	0.642	0.42	6,206	8,394
2.160	1	5		1.5	CC	Yes	$ 27,460	8,403	$ 134,879	0.672	0.45	6,119	8,546

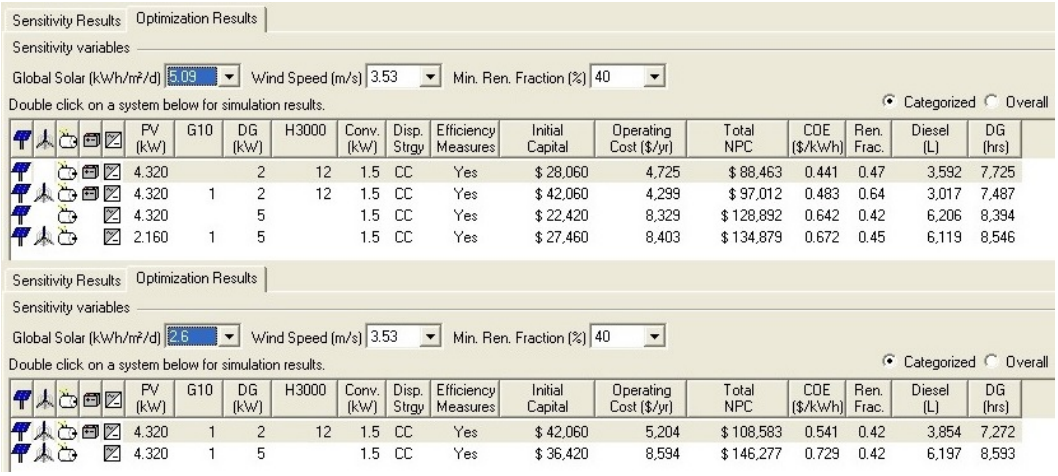
Figure 2.15: System design for Minimum Renenewable Fraction (%) of 0%, 20% and 40%

The other two sensitivity variables are fixed:

- 5,09 kWh/m2 annual average of daily radiation and 3,53 m/s annual average wind speed.

25% is the maximum renewable fraction for the minimum NPC system with no constraints to assure a minimum percentage of renewable energy, see tables of values in 2.15. This system is a PV/Diesel/Battery system with a COE of 0,436 USD/kWh. Notice that the economic results of the Diesel/Battery system, 0% of renewable, are worse than mentioned earlier. Clean technologies may be more cost-effective than traditional only fuel based systems in some scenarios.

When the system is defined to assure a relevant minimum percentage of renewable (40%) the PV system design is increased (from 2,16 kW to 4,32 kW) up to its maximum capacity (taking into account the space constraints



Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 5.09 | Wind Speed (m/s) 3.53 | Min. Ren. Fraction (%) 40

Double click on a system below for simulation results. ⦿ Categorized ○ Overall

PV (kW)	G10	DG (kW)	H3000	Conv. (kW)	Disp. Strgy	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
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2.160	1	5		1.5	CC	Yes	$ 27,460	8,403	$ 134,879	0.672	0.45	6,119	8,546

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 2.6 | Wind Speed (m/s) 3.53 | Min. Ren. Fraction (%) 40

Double click on a system below for simulation results. ⦿ Categorized ○ Overall

PV (kW)	G10	DG (kW)	H3000	Conv. (kW)	Disp. Strgy	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
4.320	1	2	12	1.5	CC	Yes	$ 42,060	5,204	$ 108,583	0.541	0.42	3,854	7,272
4.320	1	5		1.5	CC	Yes	$ 36,420	8,594	$ 146,277	0.729	0.42	6,197	8,593

Figure 2.16: Solar resource sensitivity for 5,09 and 2,6 kWh/m2.

in the building). This PV/Diesel/Battery system with the maximum PV installation assures up to 47% of renewable.

This scenario comparison also shows that the maximum renewable fraction is 64%, and it is the PV/Wind/Diesel/Battery system. The NPC of this greener system is only 9,7% higher than the PV/Diesel/Battery system that assures up to the 47% of the energy RES-based.

System design sensitivity to Solar source (Daily Radiation in kWh/m2)

The values for this sensitivity variable are: 5,09 and 2,6 kWh/m2. These are the expected results:

- In the first case (5,09 kWh/m2), the optimal system is defined using the annual average of daily radiation according to the solar resource availability of the defined site.

- In the second case (2,6 kWh/m2), systems that will be optimized to operate in the worst case, corresponding to the month of December will be shown.

The other two sensitivity variables are fixed:

- 3,53 m/s annual average wind speed and 40% of minimum renewable fraction.

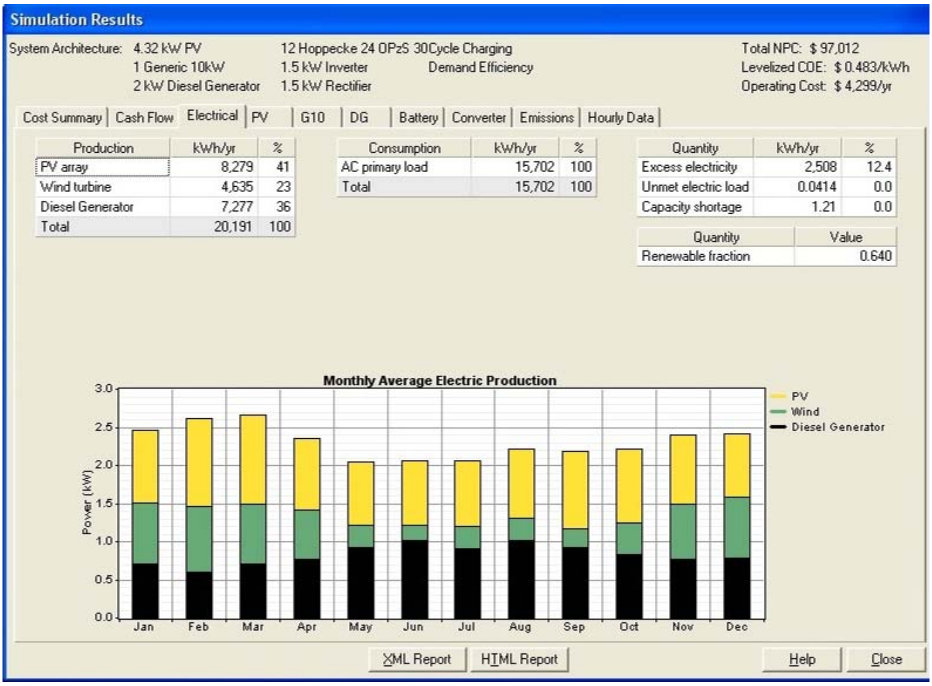


Figure 2.17: Solar energy contribution to the electrical production of the PV/Wind/Diesel/Battery system (kW) (monthly average)

The optimal PV/Wind/Diesel/Battery system (minimum NPC criteria) produces more expensive energy when it is working with a minimum availability of solar resource, as shown in 2.16. The energy produced in the month of December is 12% more expensive than the expected cost with the annual average availability of solar resource (COE around 0,541 USD/kWh in December versus 0,483 USD/kWh), see figure 2.17.

The optimal PV/Wind/Diesel/Battery system (minimum NPC criteria) in the worst case of solar availability correspond to the system that provides the maximum renewable fraction of 64% with the annual average renewable resources availability, already identified in the previous sensitivity analysis.

Within this system, the main contribution of renewable resources corresponds to solar (41% as shown in the following image) and that is why the analysis revealed a relevant sensitivity to the availability of this resource.

System design sensitivity to Wind resource (Wind speed in m/s)

The values for this sensitivity variable are: 3,53 and 2,9 m/s. These are the expected results:

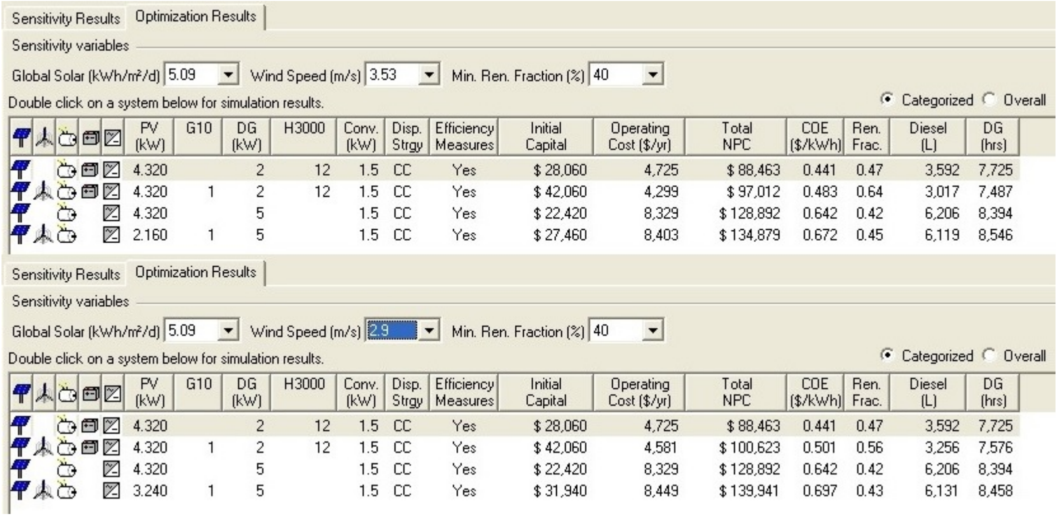
- In the first case (3.53 m/s), the optimal system is defined using the annual average of wind speed according to the wind resource availability of the defined site.
- In the second case (2,9 m/s), there would be systems that will be optimized to operate in the worst case, corresponding to the month of June.

The other two sensitivity variables are fixed:

- 5,09 kWh/m2 annual average of daily radiation and 40% of minimum renewable fraction.

The optimal PV/Wind/Diesel/Battery system (minimum NPC criteria) working with a minimum availability of wind resource produces energy at nearly the same price, see figure 2.18. The energy produced in the month of June is 3,7% more expensive than the expected cost with the annual average availability of wind resource (COE around 0,501 USD/kWh in June versus 0,483 USD/kWh).

The optimal system, the PV/Diesel/Battery system, (minimum NPC criteria) in the worst case of wind availability is the same as that in the annual average scenario.


Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 5.09 · Wind Speed (m/s) 3.53 · Min. Ren. Fraction (%) 40

Double click on a system below for simulation results. · Categorized · Overall

PV (kW)	G10	DG (kW)	H3000	Conv. (kW)	Disp. Strgy	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
4.320		2	12	1.5	CC	Yes	$ 28,060	4,725	$ 88,463	0.441	0.47	3,592	7,725
4.320	1	2	12	1.5	CC	Yes	$ 42,060	4,299	$ 97,012	0.483	0.64	3,017	7,487
4.320		5		1.5	CC	Yes	$ 22,420	8,329	$ 128,892	0.642	0.42	6,206	8,394
2.160	1	5		1.5	CC	Yes	$ 27,460	8,403	$ 134,879	0.672	0.45	6,119	8,546

Sensitivity Results | Optimization Results

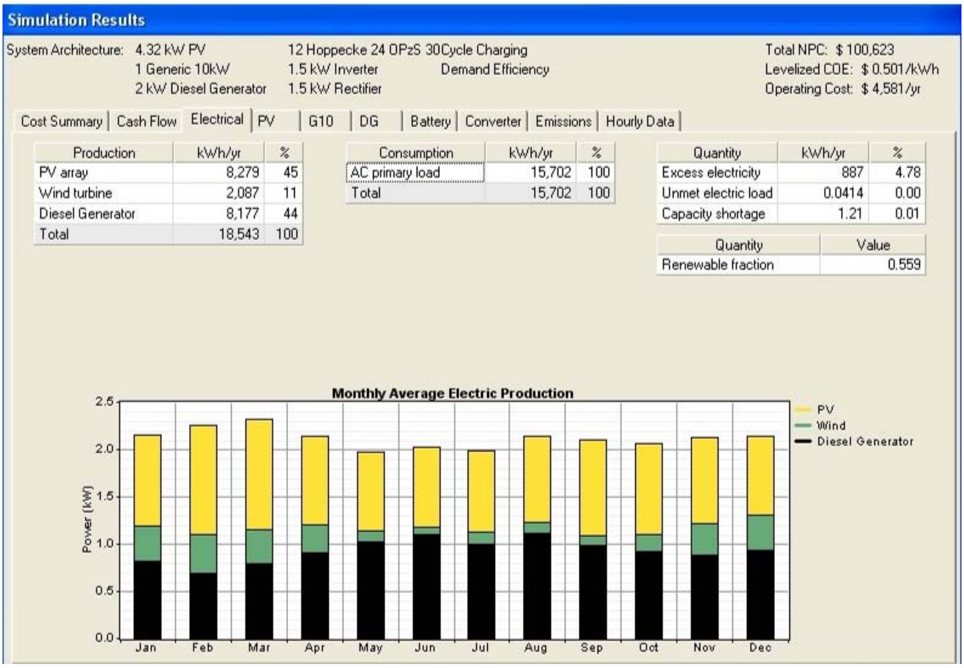
Sensitivity variables

Global Solar (kWh/m²/d) 5.09 · Wind Speed (m/s) 2.9 · Min. Ren. Fraction (%) 40

Double click on a system below for simulation results. · Categorized · Overall

PV (kW)	G10	DG (kW)	H3000	Conv. (kW)	Disp. Strgy	Efficiency Measures	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
4.320		2	12	1.5	CC	Yes	$ 28,060	4,725	$ 88,463	0.441	0.47	3,592	7,725
4.320	1	2	12	1.5	CC	Yes	$ 42,060	4,581	$ 100,623	0.501	0.56	3,256	7,576
4.320		5		1.5	CC	Yes	$ 22,420	8,329	$ 128,892	0.642	0.42	6,206	8,394
3.240	1	5		1.5	CC	Yes	$ 31,940	8,449	$ 139,941	0.697	0.43	6,131	8,458

Figure 2.18: Wind resource sensitivity for 3,53 and 2,9 m/s


Simulation Results

System Architecture: 4.32 kW PV · 1 Generic 10kW · 2 kW Diesel Generator · 12 Hoppecke 24 OPzS 3000 · 1.5 kW Inverter · 1.5 kW Rectifier · Cycle Charging · Demand Efficiency

Total NPC: $ 100,623 · Levelized COE: $ 0.501/kWh · Operating Cost: $ 4,581/yr

Cost Summary | Cash Flow | Electrical | PV | G10 | DG | Battery | Converter | Emissions | Hourly Data

Production	kWh/yr	%
PV array	8,279	45
Wind turbine	2,087	11
Diesel Generator	8,177	44
Total	18,543	100

Consumption	kWh/yr	%
AC primary load	15,702	100
Total	15,702	100

Quantity	kWh/yr	%
Excess electricity	887	4.78
Unmet electric load	0.0414	0.00
Capacity shortage	1.21	0.01

Quantity	Value
Renewable fraction	0.559

Figure 2.19: Wind energy contribution to the electrical production of the PV/Wind/Diesel/Battery system (kW) (monthly average)

		ENERGY MODEL				OPTIMISATION CRITERIAS						
		CONV. GENERATION	RENEWABLE GENERATION		STORAGE	ENVIROMENTAL		ECONOMICAL		TECHNICAL		
POWER SYSTEMS		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**	A
	PV_DIESEL_BATTERY	**2**	**4.320**	**0**	**12**	**0.47**	**9,46**	**88,463**	**0.441**	**6,345**	**116**	C
	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**	B
	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	

Figure 2.20: Scenarios with summary of influence for different design criteria

The contribution of wind energy to the PV/Wind/Diesel/Battery system is very little, as described in figure 2.19, 11% as an annual average.

Other different scenarios could be suggested with other different variables such as the critical load.

2.3.5 Scenarios for different design criteria

The design criteria selection determines different optimal designs for the hybrid renewable power system. In figure 2.20 for each optimization criteria the two worst cases are marked in red and two best ones in green.

The influence among the different optimization criteria for the case study can be summarized as follows:

- The NPC is one optimization criteria with economic aspects, and the unique one used by HOMER software. However, it does not take directly into account the environmental benefits via the maximum renewable fraction or minimize CO2 emissions.

  Prioritising the economic criteria (both NPC and COE) scenario A is the optimal one: PV(2,16 kW)/ Diesel(2 kW)/ Battery(12x3.000 Ah), that produces energy at a 0,436 USD/kWh cost.

- The environmental optimization criteria are correlated, the maximum renewable fraction is the minimum CO2 emissions.

Prioritising the environmental criteria (renewable fraction and CO2 emissions) scenario B is the optimal one: PV(4,32 kW)/ Wind(10 kW)/ Diesel(2 kW)/ Battery(12x3.000 Ah), that represents a renewable fraction of 64%.

- There are some other technical criteria that should be taken into account.

  For instance, the "Battery throughput" should be maximized because when installing a bank of batteries they are meant to be a relevant active part of the system. If not, there would be a risk of over-sizing the storage system and negatively affecting the economic results of the system.

  In a similar way, the excess of electricity could be minimized in order not to oversize the generation system and negatively affect the economic results of the system.

  The prioritisation of the technical criteria does not conclude any optimal scenario in the studied case.

Finally, if we take a global overview of the different criteria (economic, environmental and technical) the system that combines better indicators is:

- Scenario C: PV(4,32kW)/ Diesel(2 kW)/ Battery(12x3.000 Ah) system.

This hybrid system produces energy at 0,441 USD/kWh with a renewable fraction of 47%.

2.4 Summary of main contributions of the proposed case study

After a first brief revision of the design state-of-the-art valid for the period 2005-2015 several references have been included in relation to the design of stand-alone hybrid renewable power systems. These studies identified in the review are mainly focused on isolated communities (an Indian village or an isolated community in the Amazon) or islands (community with less than 100 houses in Australia, for instance). Some of these systems are very similar to the concept of smart grid, where the system as a whole is designed to be able to operate on island mode, off-grid. Some of these studies develop a case study but they usually optimize one economic criteria, usually depending on the design tool used (like in HOMER where optimization criteria is the NPC). Very few of those studies take into account other criteria like environmental or public policy influences (subsidies, public incentives or penalties).

The main contributions of the case study proposed in this chapter are:

- a case study based on a telecommunication center based in the province of Tarragona (Spain);
- the comparison of different scenarios of optimal stand-alone hybrid renewable system design depending on different optimization criteria: economic, environmental and technical;
- an analysis of the sensitivity of the optimal system design to the availability of renewable resources;
- the integration of several design tools and information databases (HOMER, RETScreen and PVsyst) in the case study;

2.5 Conclusions about the design criteria sensitivity

The case study analysed in the present chapter shows up that the optimization of economic criteria (independently to the economic variable or the objective function) does not directly provide the optimal design for the renewable hybrid power system according as far as other very relevant factors such as environmental (as CO2 emissions) or technical aspects would suggest more optimal scenarios. For this case study, taking a global overview of the different criteria (economic, environmental and technical) the hybrid system that combines better indicators is scenario C: PV(4,32kW)/ Diesel(2 kW)/ Battery(12x3.000 Ah) system. This hybrid renewable energy system would produce energy at 0,441 USD/kWh with a renewable fraction of 47%.

This case study has been developed with tools and information resources public available on internet (software design, renewable resources data, product databases, etc). The accessibility to design tools is not a barrier nowadays, however a training investment is required, a minimum technical knowledge and the capacity to properly combine and take advantage of the different benefits from each tool.

The renewable energy sector has gained a lot of support in the last decade. Mostly due to climate change mitigation strategies and technological advances. Therefore, there is an increasing literature and interest on hybrid renewable solutions.

In order to contribute to the global trend for greener energy and more accessibility to electricity world-wide, namely Sustainable Energy for All (SE4All), research community has a promising role to contribute to a sustainable world development.

Up to now, the wide-range of variables that influences in the design and control of hybrid renewable systems, some of them analysed in the case study and the available design tools suggests that there is a relevant need to improve the research conducted in this field. The next step would be to identify the opportunity of providing a more optimal design methodology beyond economic criteria for renewable hybrid power systems with user-friendly and widely accessible tool.

Chapter 3

Scanning innovations introducing renewable energy sources off-grid

After defining the scope of the problem of sustainable energy access and the research objectives regarding HRES in chapter 1, and identifying the main design criteria for the hybridization with renewable energy via a case study in chapter 2, this chapter is devoted to scanning and learning from innovations introducing renewable energy sources off-grid with a broader scope beyond techno-economic criteria with a world-wide scope.

In order to scan most relevant innovations in the recent years, a searching methodology is proposed. After building up a first primary database of almost 400 entries, an overview of main insights is provided regarding: the characterization of innovation publication, main renewable source of energy, different configurations, back-up systems, categories in techno-economic design identifies, different applications and countries, among many other perspectives as detailed in the following sections.

3.1 Searching methodology scanning innovations on renewable energy sources off-grid

Identify, search and analyse iteratively in order to: build up a primary database of innovations in HRES, and provide a searching methodology for future developments.

3.1.1 Building the primary database of innovations in HRES

- Identify 'keywords' related to HRES terms and definitions: Standalone, Hybrid Renewable Energy (or Power) System, Renewable Energy sources, Solar energy, Wind energy, Diesel generator, Off-grid, Remote, Islanded, Microgrid, Mini-grid, Autonomous power system,Energy hubs, etc.

- Search 'keywords' in research publications databases (Elsevier, IEEE, others). Find peer reviewed research publications. Search 'keywords' in open search engines (Google). Find projects/ products/ companies/ organizations.

- Analyse content and identify relevant categories (research focus, energy sources, storage systems, main applications, real-life installations, etc)

- Relevant content for HRES innovations. If yes, then: Introduce publication in the primary database indicating: source identification. Introduce publication's relevant categories.

3.1.2 Flowchart of the database building process

In figure 3.1 the flowchart of the building process of the primary database of HRES innovations is described.

3.1.3 Database structure

Introduce publication in the primary database indicating: source identification.

Source identification:

- Name of the research publication.

- Type of publication: Journal, Conference, Chapter/ book/ report/ post, PhD, Project.

- Year of publication, period 2005 to 2015

- Country of the publishing institution.

- Title and citation text.

- Number of references and citations (2013, 2014, 2015).

- Authors email.

- Link.

Relevant categories for "Terms and definitions":

- Stand-alone Hybrid Renewable Energy (or Power) System

- Off-grid, remote or islanded

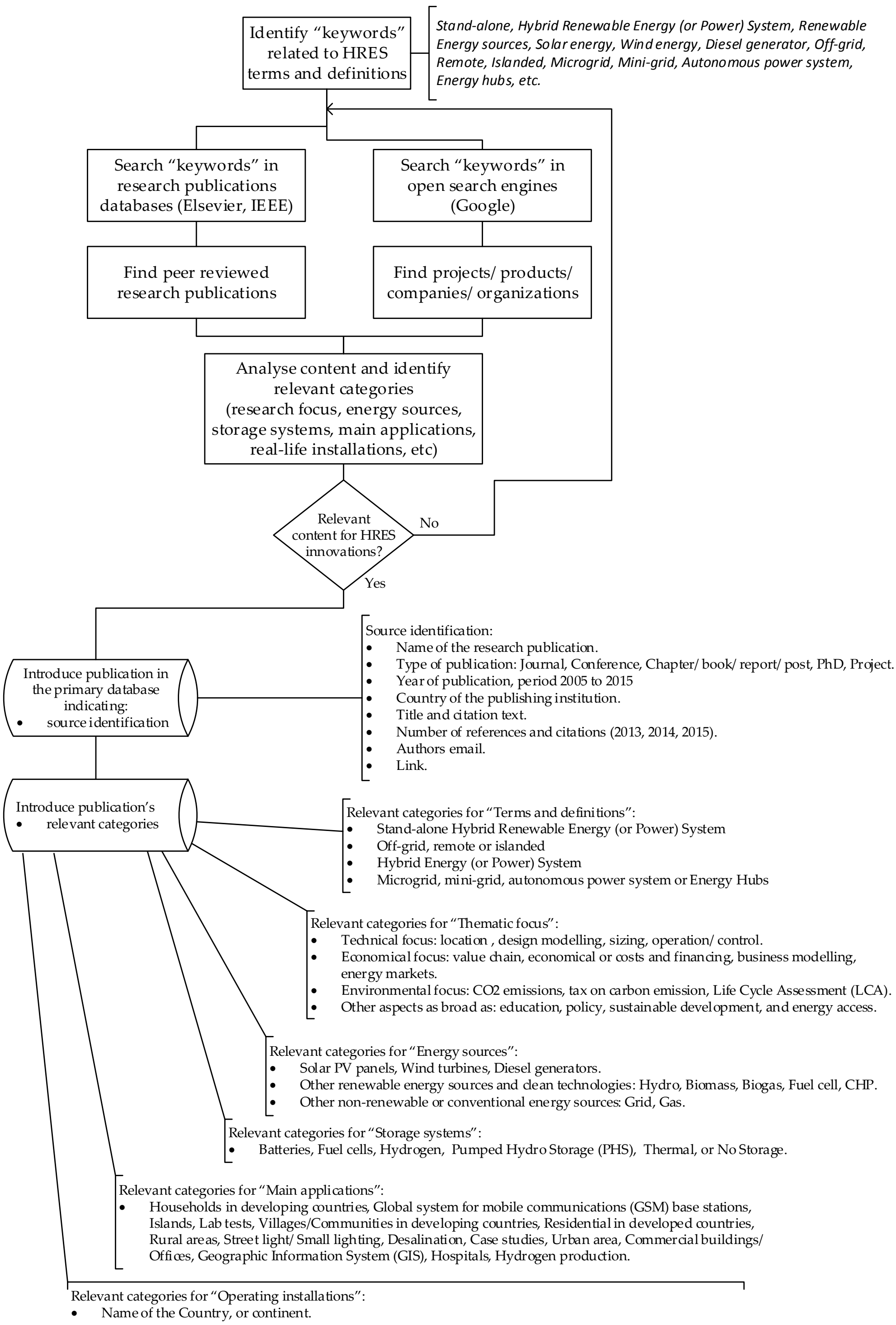


Figure 3.1: Flowchart of the building process of the primary database of HRES innovations (387 publications)

- Hybrid Energy (or Power) System
- Microgrid, mini-grid, autonomous power system or Energy Hubs

Relevant categories for "Thematic focus":

- Technical focus: location , design modelling, sizing, operation/ control.
- Economic focus: value chain, economic or costs and financing, business modelling, energy markets.
- Environmental focus: CO2 emissions, tax on carbon emission, Life Cycle Assessment (LCA).
- Other aspects as broad as: education, policy, sustainable development, and energy access.

Relevant categories for "Energy sources":

- Solar PV panels, Wind turbines, Diesel generators.
- Other renewable energy sources and clean technologies: Hydro, Biomass, Biogas, Fuel cell, CHP.
- Other non-renewable or conventional energy sources: Grid, Gas.

Relevant categories for "Storage systems":

- Batteries, Fuel cells, Hydrogen, Pumped Hydro Storage (PHS), Thermal, or No Storage.

Batteries, Fuel cells, Hydrogen, Pumped Hydro Storage (PHS), Thermal, or No Storage.

Relevant categories for "Main applications":

- Households in developing countries, Global system for mobile communications (GSM) base stations,
- Islands, Lab tests, Villages/Communities in developing countries, Residential in developed countries,
- Rural areas, Street light/ Small lighting, Desalination, Case studies, Urban area, Commercial buildings/
- Offices, Geographic Information System (GIS), Hospitals, Hydrogen production.

Relevant categories for "Operating installations":

- Name of the Country, or continent.

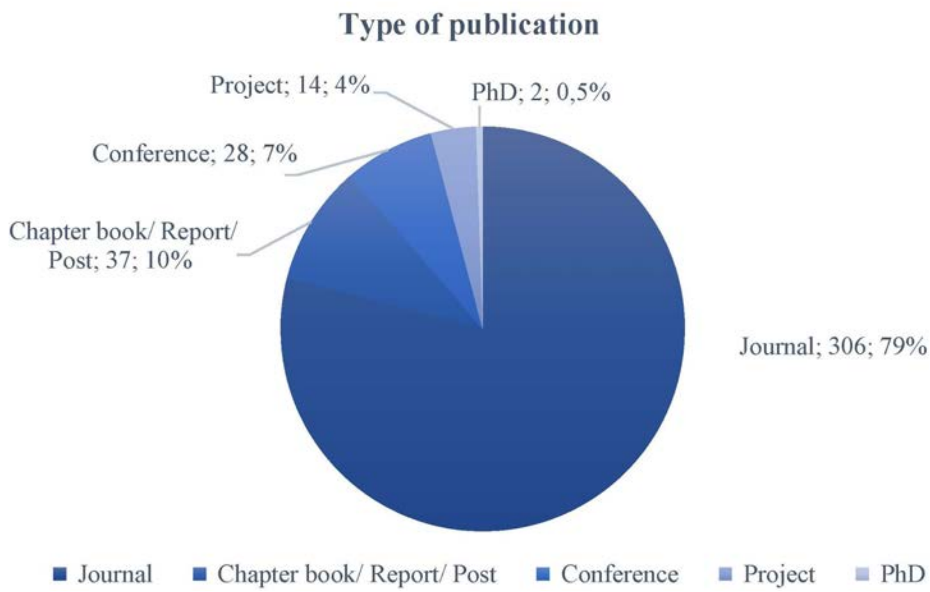


Figure 3.2: Number of publications per types (total 387)

3.1.4 Database content overview

The total number of innovations in HRES is 387 contained in the primary database for the period 2005-2015. A detailed analysis is provided below regarding:

Supportive to this analysis, [91] review also includes more than 350 references from 14 Elsevier journals for related articles within the period from 2000 until 2014 contributing with insights supporting the findings detailed below. This study is framed in the UNESCO chair in Energy for Sustainable Development.

The 387 innovations in the primary database correspond to multiple publication types, as described in figure 3.2. Those publications are mostly in journals (306, 79%), chapters of books or reports (37, 10%), conferences (28, 7%), projects (14, 4%) and PhD thesis (2, 0,5%).

A total of 359 of the publications in the primary database belong to the period from 2005 to 2015, as displayed in figure 3.3. Within this period, 80% of them (total of 286) have been published from 2009 to 2013. This is also the most intense period of bibliography research that has been carried out for the first part of the current thesis work.

Out of the 306 articles published in journals, 81% (total of 248) of them

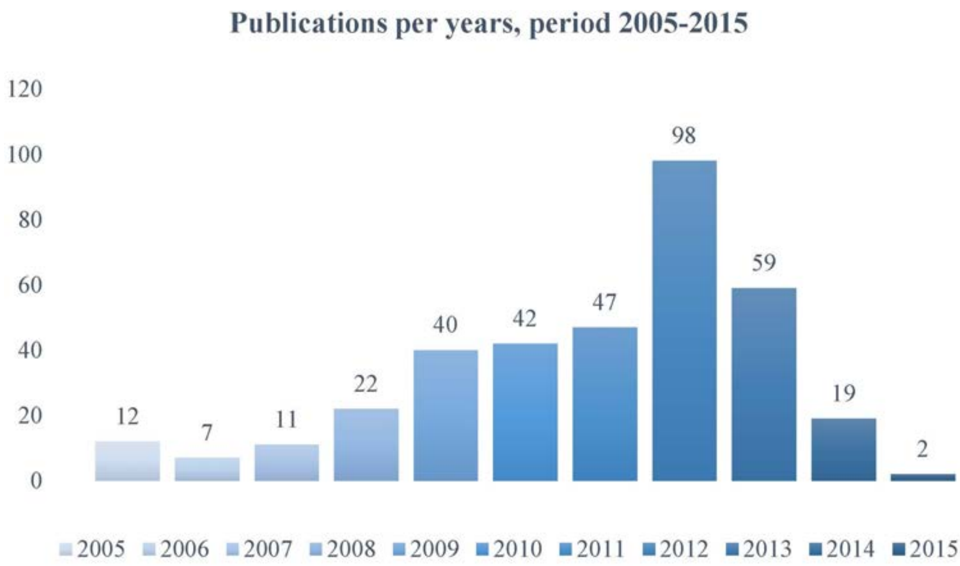


Figure 3.3: Number of publications per years, during the period 2005-2015 (total 359)

are published in 10 journals. There are a total of 52 different journals present in the primary database contributing different approaches of innovation in HRES. Only 10 of them publish the vast majority of innovations present in the primary database. As shown in figure 3.4 the top 10 journals for innovations in HRES are:

1. Renewable and Sustainable Energy Reviews (56 articles, 18%)
2. Renewable Energy (44 articles, 14%)
3. Applied Energy (30 articles, 10%)
4. Energy Policy (30 articles, 10%)
5. Energy (20 articles, 7%)
6. Energy for Sustainable Development (19 articles, 6%)
7. Solar Energy (17 articles, 6%)
8. International Journal of Electrical Power and Energy Systems (14 articles, 5%)

9. Energy Conversion and Management (11 articles, 4%)

10. International Journal of Hydrogen Energy (7 articles, 2%)

The articles of the top 10 journals have an average of 49 references. Shown in more in detail with the average per each journal in figure 3.5, "Renewable and Sustainable Energy Reviews" (number 1 journal) presents the maximum average with 81 references. The minimum average of references is 31 for the articles in both "Renewable Energy" (number 2 journal) and "International Journal of Hydrogen Energy" (number 10 journal).

From 51 to 267 references is the maximum number of references found within the top 10 journals. 267 is the highest number of references in an article accessible in "Renewable and Sustainable Energy Reviews" (top 1 journal). While the minimum number of references are from 0 to 18, this is quite below the average of 49 references of the top 10 journals. In figure 3.6 there is a table and a graph with the detailed information of the minimum, maximum and average of references for the total number of articles per each of the top 10 journals.

As for the number of citations, the top 20 for the year 2015 have been analysed. 500 citations point the most popular article in the primary database that focus on "Energy storage systems - Characteristics and comparisons". The second most cited article, with 366 citations in 2015, is "Social acceptance of renewable energy innovation: An introduction to the concept". Its popularity in 2015 is followed closely by an article related to computer tools review (344 citations) and another one related to the diffusion of renewable energy technologies(321 citations), as it can be observed in figure 3.7. It is relevant for the integrated approach of this PhD work that in the top 4 most popular articles there are 2 technical and 2 non-technical related research works.

64 countries are present in the primary database of innovations related to HRES. In figure 3.8 it is plotted each of those countries with the number of research publications identified and ordered by the national electrification rate (in %). A low number of research publications can be observed by Universities or Research centers in countries with electrification under 85%. A total of 48 publications, 15% out of a total of 328 in the period 2005-2015, correspond to those countries with high electrification needs.

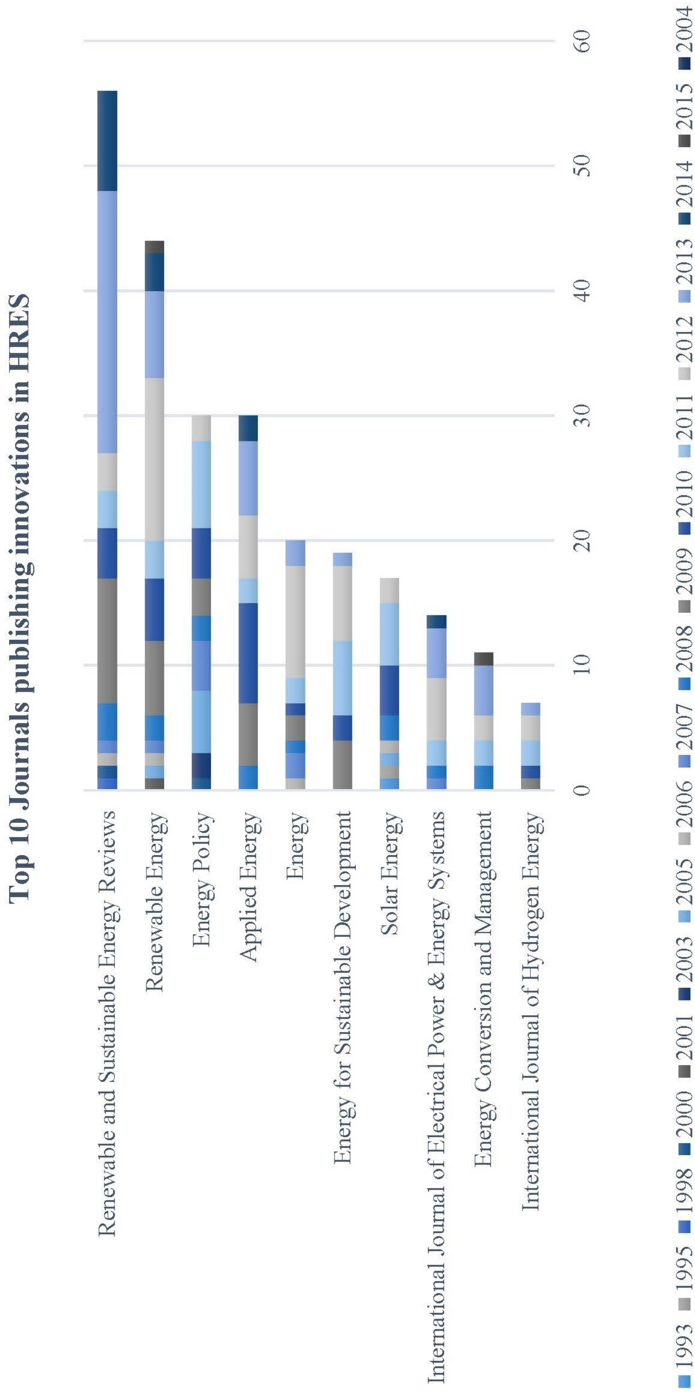


Figure 3.4: Top 10 journals publishing innovations in HRES (total 248 articles)

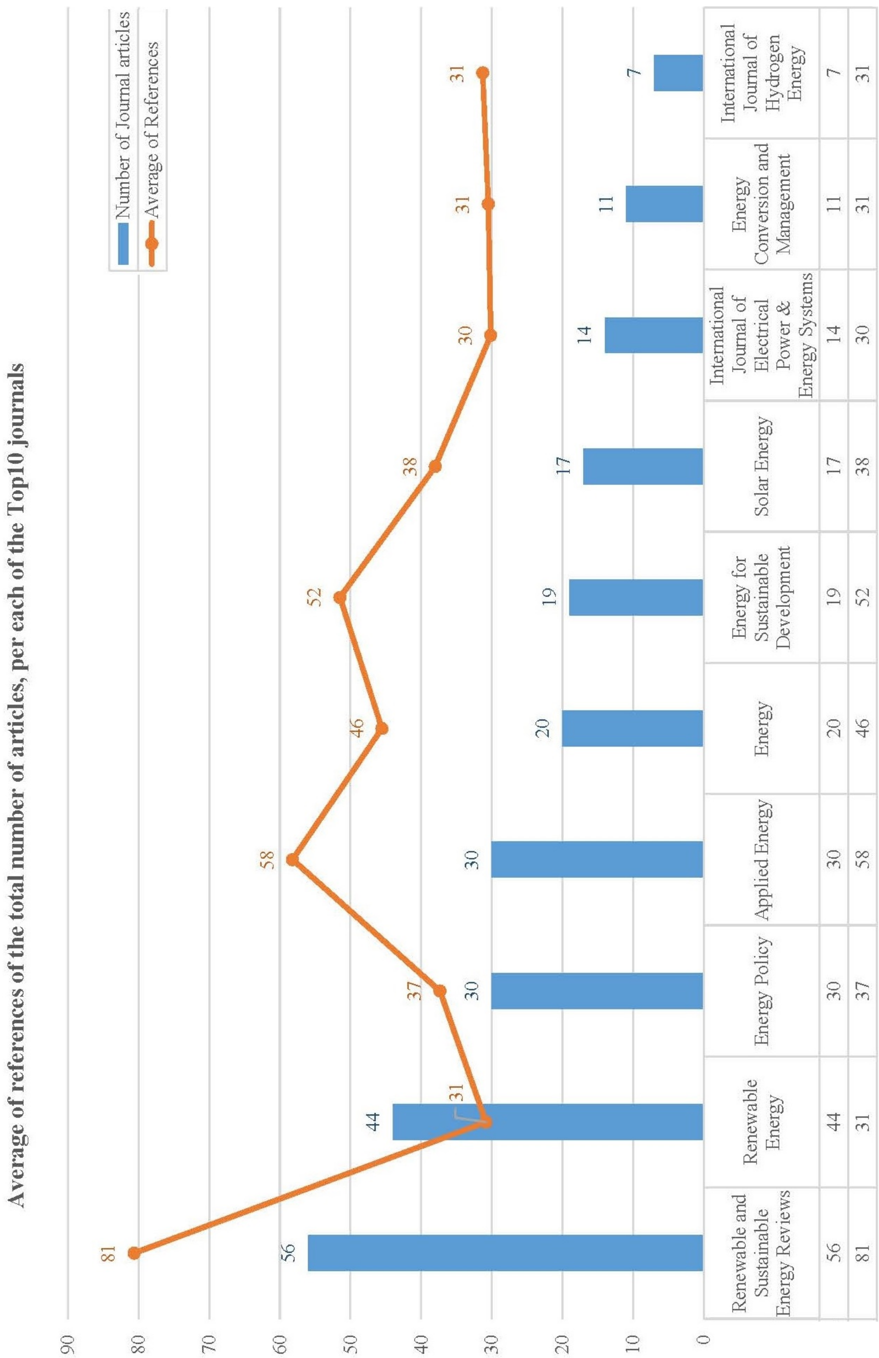
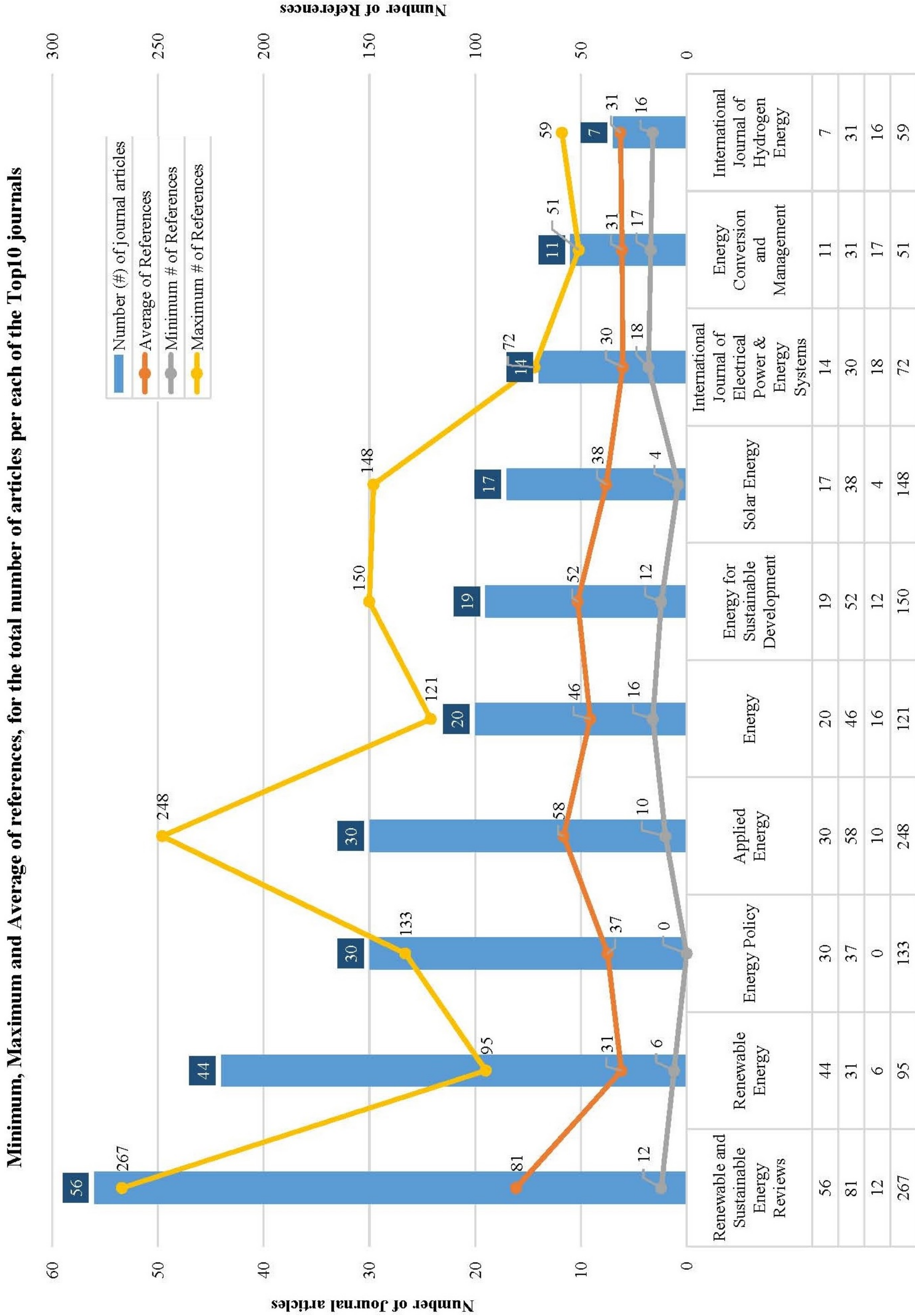


Figure 3.5: Average of references of the total number of articles, per each of the Top 10 journals (total 248 articles with 49 references in average)



	Renewable and Sustainable Energy Reviews	Renewable Energy	Energy Policy	Applied Energy	Energy	Energy for Sustainable Development	Solar Energy	International Journal of Electrical Power & Energy Systems	Energy Conversion and Management	International Journal of Hydrogen Energy
Number (#) of journal articles	56	44	30	30	20	19	17	14	11	7
Average of References	81	31	37	58	46	52	38	30	31	31
Minimum # of References	12	6	0	10	16	12	4	18	17	16
Maximum # of References	267	95	133	248	121	150	148	72	51	59

Figure 3.6: Minimum, Maximum and Average of references for the total number of articles per each of the top 10 journals (total 248 articles with 49 references in average)

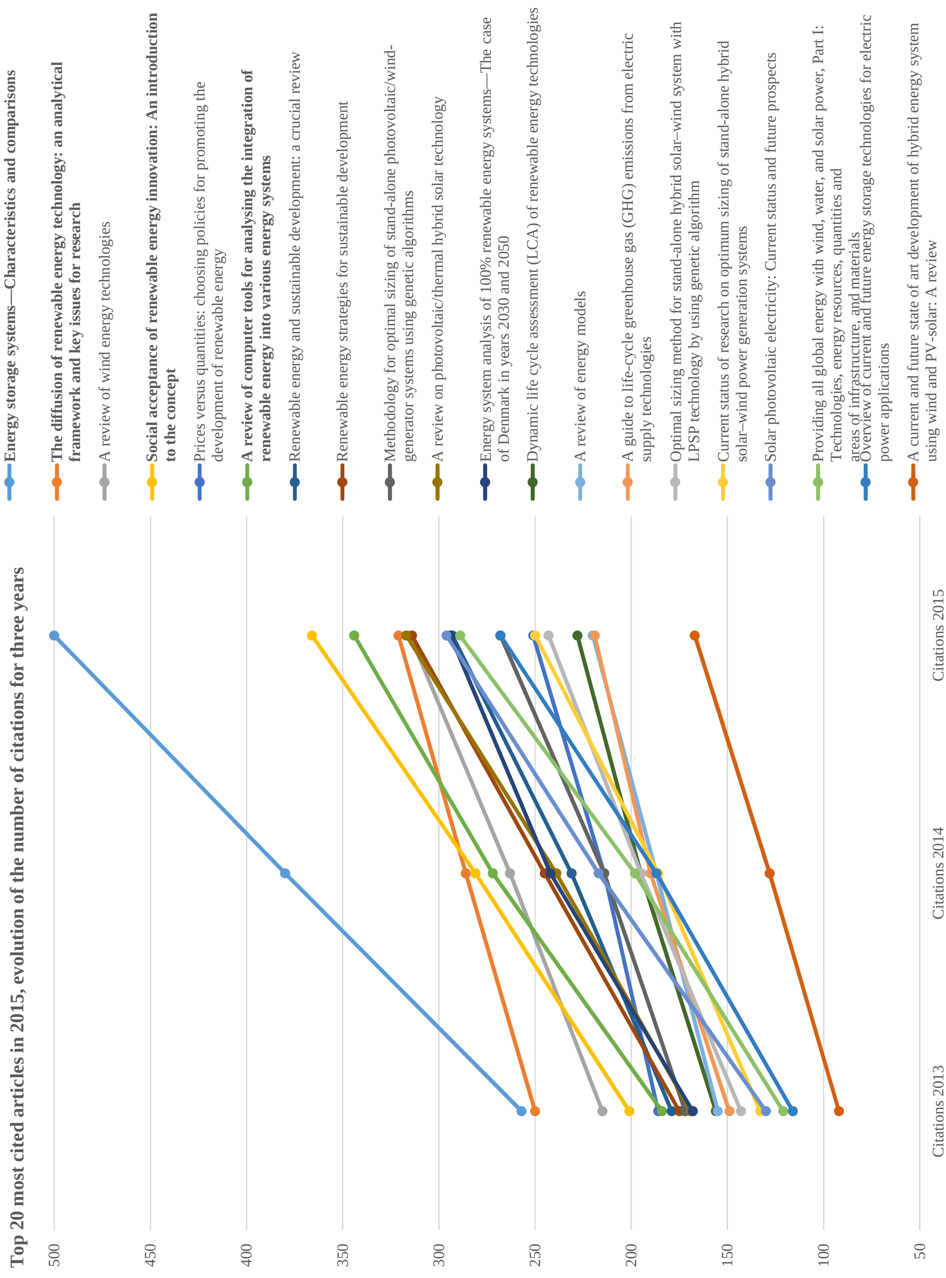


Figure 3.7: Top 20 most cited articles in 2015, evolution of the number of citations for three years

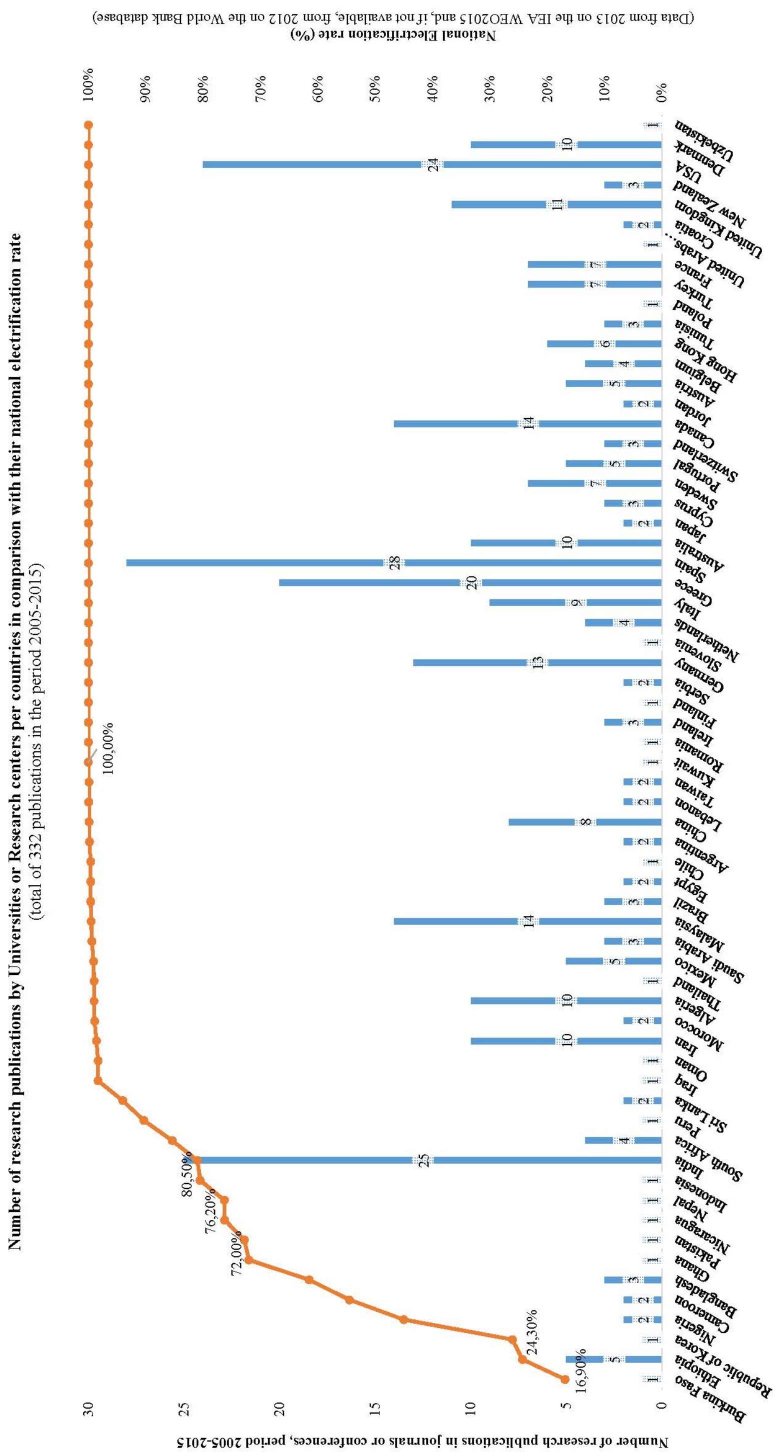


Figure 3.8: Top 20 most cited articles in 2015, evolution of the number of citations for three years

3.2 Energy sources, hybrid configurations and storage in HRES

This section presents an in depth analysis of innovations regarding the system design for Hybrid Renewable Energy Systems (HRES). In first place a description of the most predominant energy sources, different hybrid configurations and the most popular storage systems are provided.

The analysis of the latest innovations cover the current system design criteria, integrating technical, economic and more recently environmental aspects.

This chapter identifies the potential research gaps to be covered by future tools for decision-making that integrate complementary aspects in order to facilitate the massive roll-out of HRES.

3.2.1 Most predominant energy sources

Solar, Wind and Diesel are the most predominant energy sources in HRES research publications. As it can be observed in figure 3.9, Solar PV is the energy source most present in HRES publications with 72 out of 87. Wind is present as an energy source in 64 publications and Diesel generators in a total of 41.

The review also identifies PV being the most investigated generation technology in stand-alone renewable energy systems [91].

Other renewable energy sources and clean technologies are also present as: Hydro (15), Biomass (7), Biogas (4), Fuel cell (3) or CHP (3). Other non-renewable or conventional energy sources represented in publications are: Grid (15) or Gas (2).

The evolution of the energy sources for electricity generation in HRES over recent years, displayed in figure 3.10, shows the high interest of the research community in solar and wind for hybridizing stand-alone diesel generators. Figure 3.11 includes the table detailing the number of research publications including each energy sources per year, during the period 2005-2015.

3.2.2 Different hybrid configurations of energy sources

There are plenty of possible combinations of renewable and conventional energy sources to configure HRES systems. As put forth in the previous section, Solar is the most predominant source of energy and PV the most present generation technology (83%, so 72 out of 87 publications) in HRES.

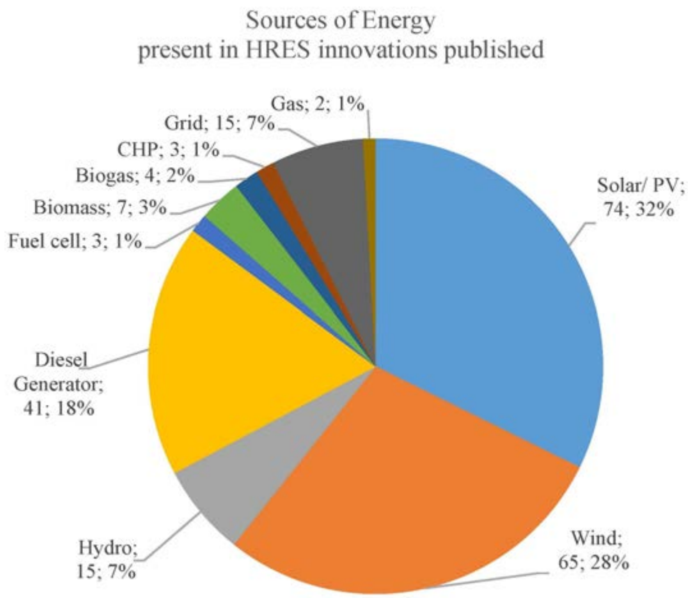


Figure 3.9: Sources of Energy present in HRES innovations published (total 87 publications)

The different HRES combinations of energy sources present in the primary database are represented in figure 3.12 and listed below, indicating the number of publications in parenthesis:

1. PV/ Wind/ Diesel (18)
2. PV/ Wind (14)
3. PV (11)
4. PV/ Diesel (7)
5. PV/ Wind/ Diesel/ Grid (6)
6. Wind/ Diesel (5)
7. PV/ Wind/ Hydro (4)
8. PV/ Hydro (3)
9. PV/ Grid (3)
10. PV/ Wind/ Grid (3)

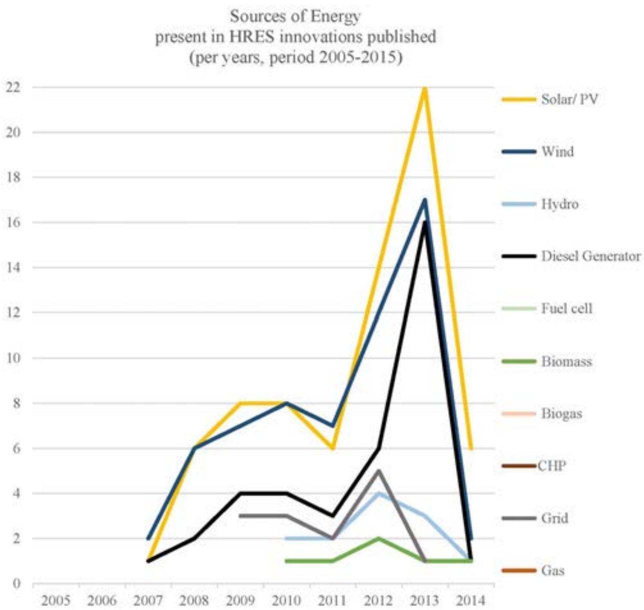
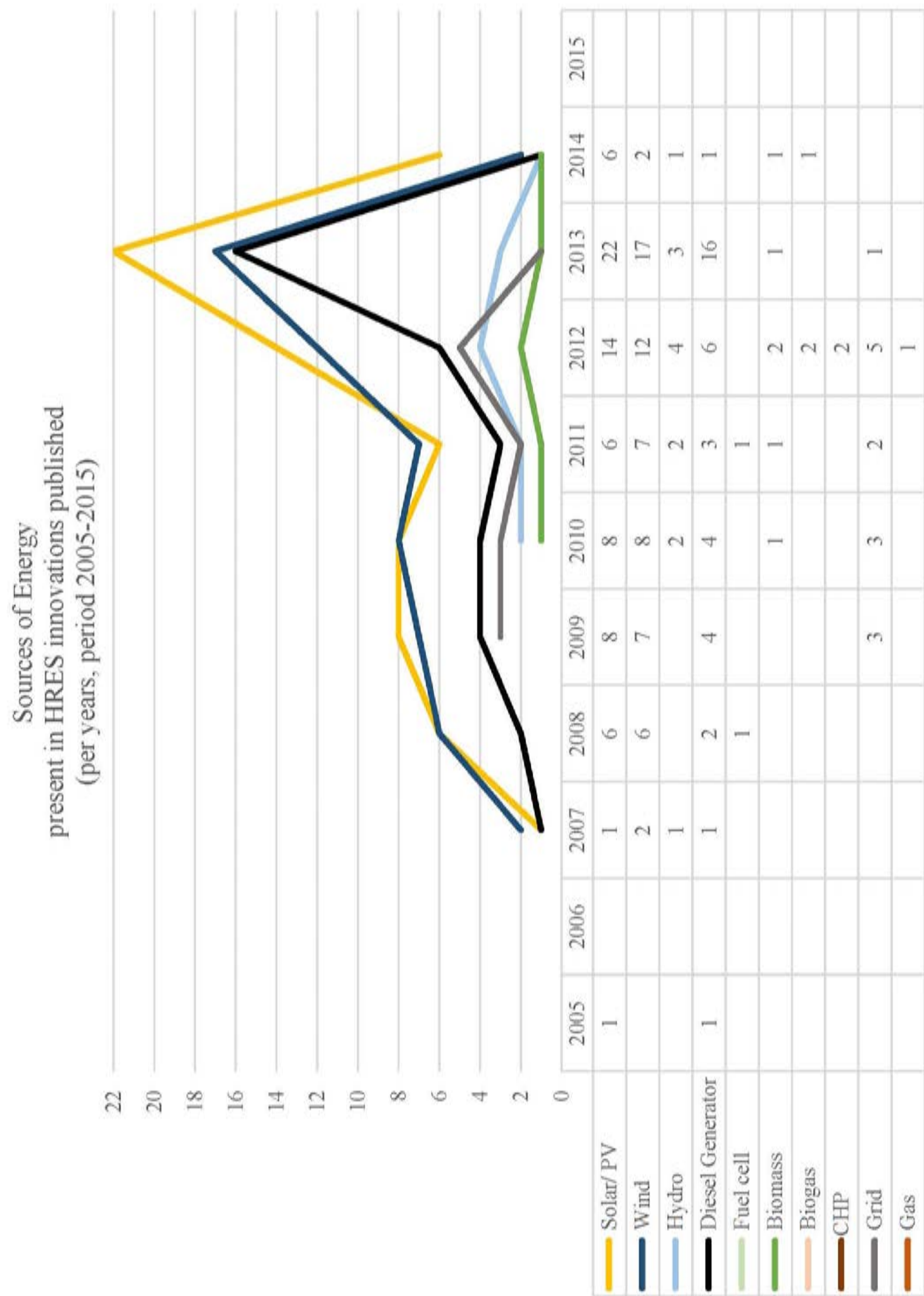


Figure 3.10: Sources of Energy for electricity generation present in HRES innovations published (per years, period 2005 - 2015) (total 87 publications)



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Solar/ PV	1		1	6	8	8	6	14	22	6	
Wind			2	6	7	8	7	12	17	2	
Hydro			1			2	2	4	3	1	
Diesel Generator	1		1	2	4	4	3	6	16	1	
Fuel cell				1			1				
Biomass						1	1	2	1	1	
Biogas								2		1	
CHP								2			
Grid					3	3	2	5	1		
Gas								1			

Figure 3.11: Sources of Energy for electricity generation present in HRES innovations published (per years, period 2005 - 2015) (total 87 publications)

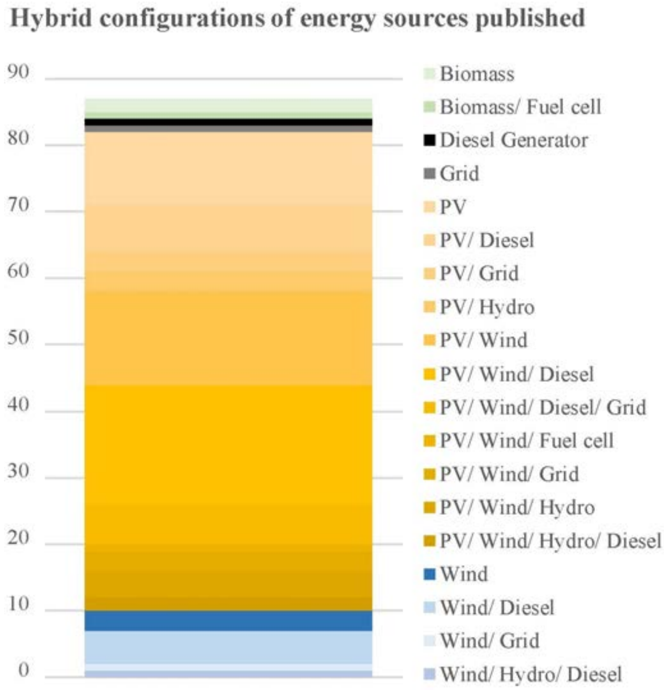


Figure 3.12: Hybrid configurations of energy sources published (total 87 publications)

11. Wind (3)
12. Biomass (2)
13. PV/ Wind/ Hydro/ Diesel (2)
14. Wind/ Grid (1)
15. Wind/ Hydro/ Diesel (1)
16. PV/ Wind/ Fuel cell (1)
17. Biomass/ Fuel cell (1)
18. Grid (1)
19. Diesel Generator (1)

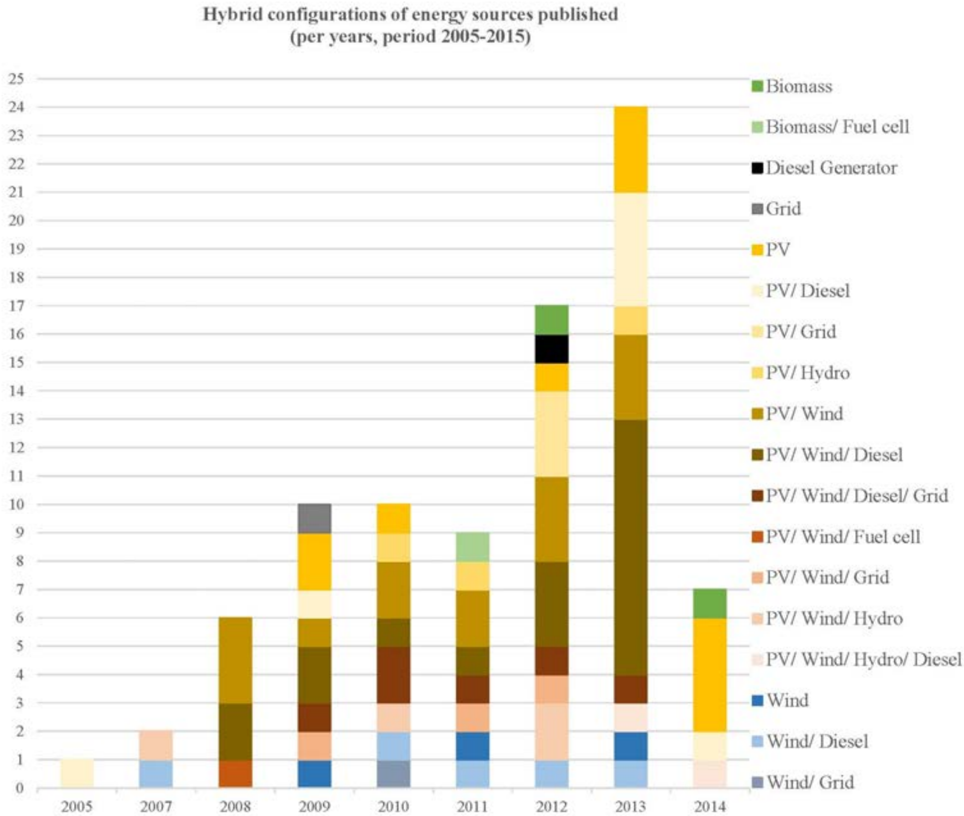


Figure 3.13: Hybrid configurations of energy sources published (per years, period 2005 - 2015) (total 86 publications)

The evolution of the hybrid configurations of energy sources in HRES over the recent years, displayed in figure 3.13, shows the high interest of the research community in solar and wind for hybridizing stand-alone diesel generators. Figure 3.14 includes a table detailing the number of research publications including each hybrid configuration per year, during the period 2005-2015.

3.2.3 Most popular storage systems

Batteries are the most predominant storage system in recent HRES research publications. A total of 58 publications in the primary database refer to storage systems in HRES. Figure 3.15 shows that Batteries are the most present storage system in those HRES publications with 47 out of 58. Fuel

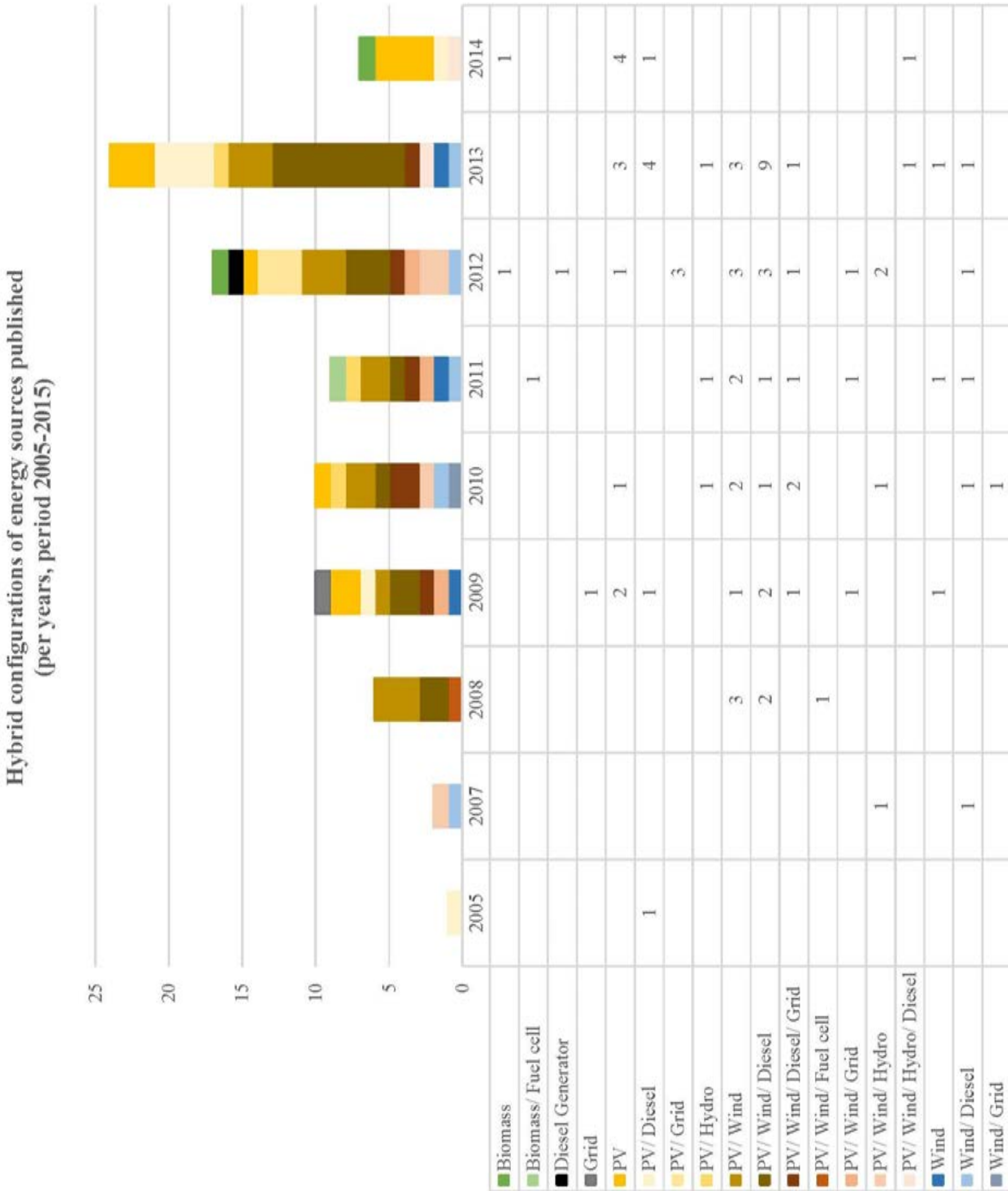


Figure 3.14: Hybrid configurations of energy sources published (per years, period 2005 - 2015) (total 86 publications)

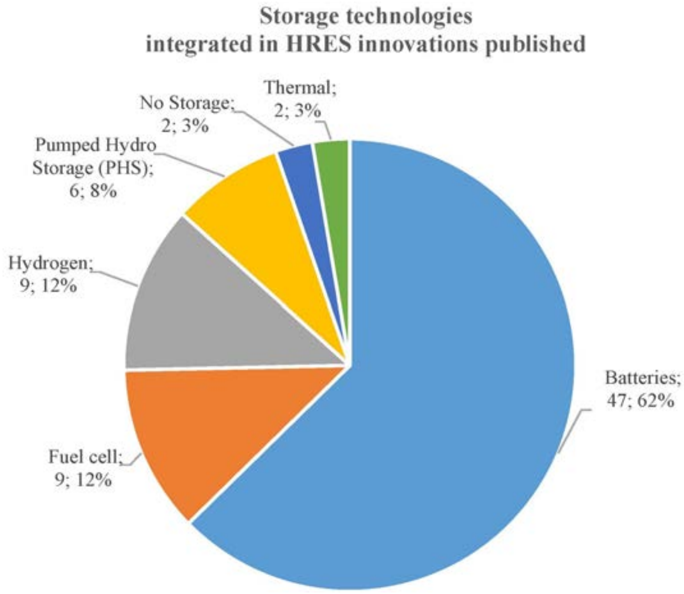


Figure 3.15: Storage systems present in HRES publications (total 58 publications)

cells are present as storage system in 9 publications and Hydrogen in a total of 9. Other storage systems for HRES are also present as: Pumped Hydro Storage (PHS) (6), Thermal (2), and others have No Storage (2).

The evolution of storage systems in HRES over recent years, displayed in figure 3.16, shows the high interest of research community in batteries for HRES. It also includes the value for the number of research publications including each storage system per year, during the period 2005-2015.

There are several possible combinations of storage systems for HRES. As advanced in the previous paragraphs, Batteries are the most predominant system but they can be present in combination with other systems. The different combinations of storage systems present in the primary database are represented in figure 3.17 and listed below, indicating the number of publications in parenthesis:

1. Batteries (39)
2. Fuel cell/ Hydrogen (4)
3. Pumped Hydro Storage (PHS) (3)
4. Batteries/ Fuel cell (3)

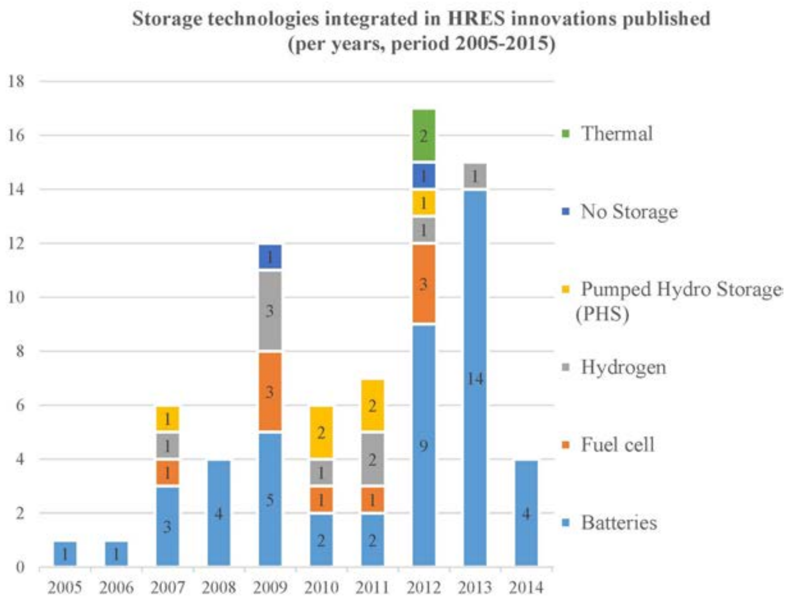


Figure 3.16: Storage systems present in HRES publications (per years, period 2005 - 2015) (total 73 publications)

5. Thermal (2)
6. No Storage (2)
7. Batteries/ Hydrogen (2)
8. Batteries/ fuel cell/ Hydrogen (1)
9. Hydrogen/ Hydro (1)
10. Batteries/ Fuel cell/ Hydrogen/ Hydro (1)

3.3 Main applications and countries

104 research publications in the primary database detail different types of applications of HRES innovations. As it can be observed in figure 3.18, main applications (and the number of publications) are: Households in developing countries (17), Global system for mobile communications (GSM) base stations (16), Islands (14), Lab tests (11) and Villages/Communities (Developing country) (11). Other main applications of HRES with less number

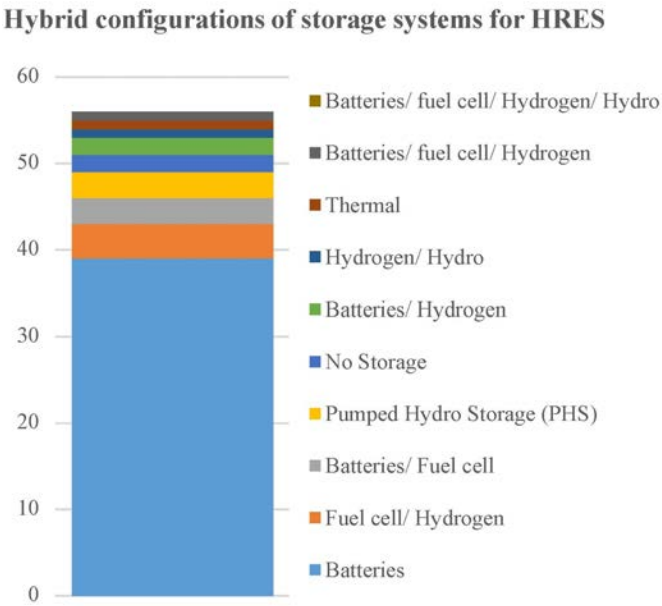


Figure 3.17: Storage systems configurations for HRES published (total 58 publications)

of research publications are: Residential in developed country) (7), Rural areas (6), Street light/ Small lighting (6), Desalination (4), Case study (4), Urban area (3), Commercial building/ Office (2), Geographic Information System (GIS) (1), Hospital (1) and Hydrogen production (1).

79 publications refer to operating installations of HRES. This means that just 20% of publications are specifically linked to real-life installations of HRES, in comparison with the total number of research publications (387) in the primary database.

Those 79 publications refer to installations in more than 35 different countries and several continents. Six countries and one continent add up together half of the publications (so 40 out of 79) as follows: Greece (11), Ethiopia (8), India (7), Africa (7), China (4) and Tunisia (3). The number of publications with operating HRES installations per country or continent is represented in figure 3.19, ordered by total number of research publications, and detailed in the list below, in alphabetical order:

- Africa (7)
- Algeria (2)

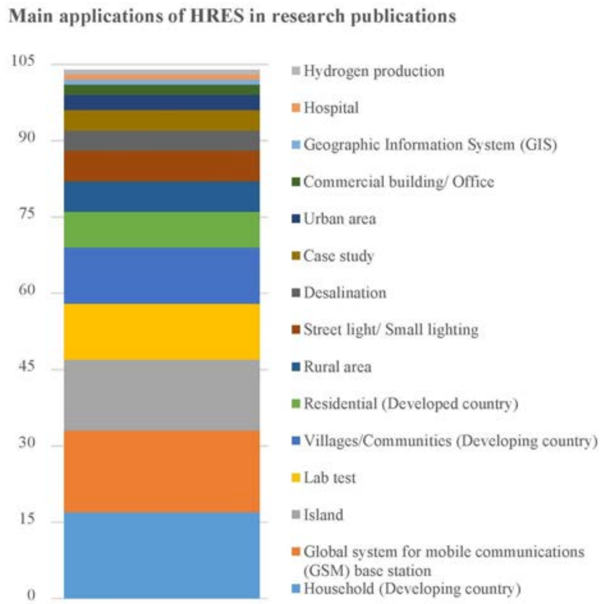


Figure 3.18: Main applications present in HRES research publications (total 104 publications)

- Argentina (2)
- Australia (1)
- Brazil (1)
- Canada (1)
- Cape Verde (1)
- Central America (1)
- China (4)
- Croatia (1)
- Denmark (1)
- Egypt (1)
- Ethiopia (8)
- Europe (1)

- France (3)
- Germany (1)
- Ghana (1)
- Greece (11)
- Hong Kong (1)
- India (7)
- Iran (2)
- Iraq (2)
- Italy (1)
- Kenya (1)
- Malaysia (1)
- Mexico (1)
- Morocco (1)
- Nicaragua (1)
- Palestina (1)
- Peru (1)
- Portugal (1)
- Romania (2)
- Saudi Arabia (1)
- Switzerland (2)
- Taiwan (1)
- Tunisia (3)
- Turkey (1)

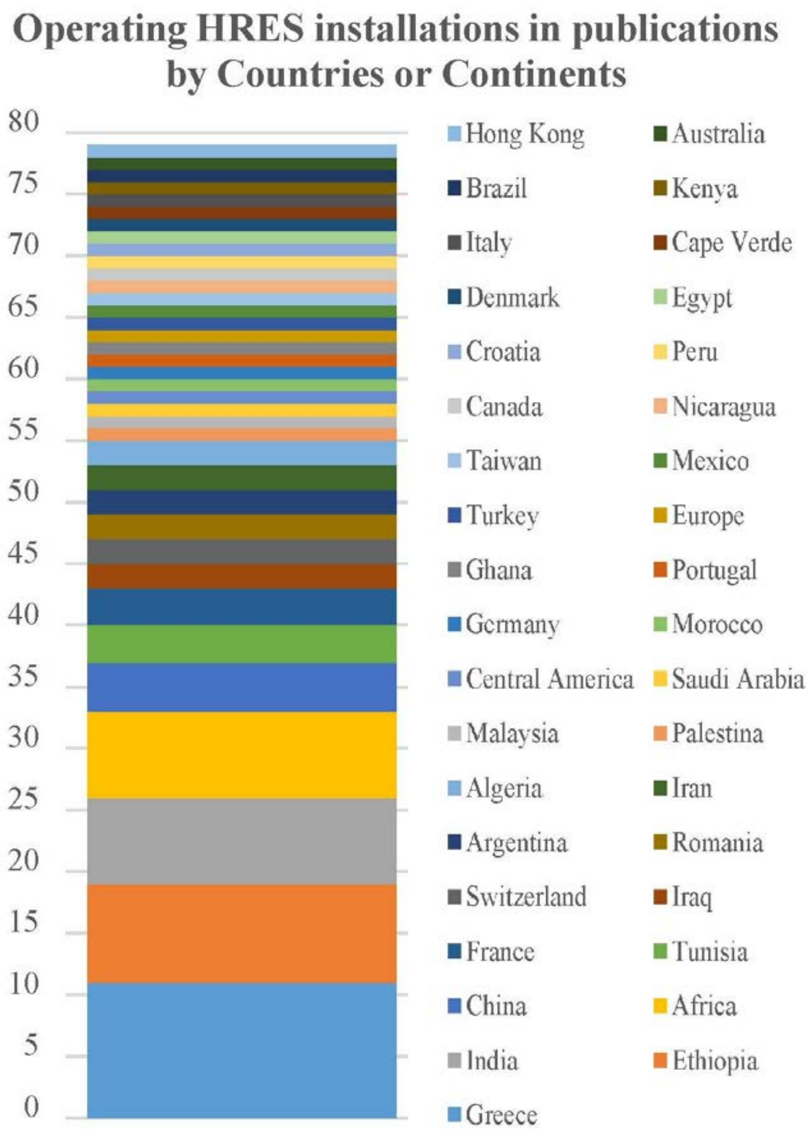


Figure 3.19: Operating HRES installations present in research publications per Countries or Continents (total 79 publications)

3.4 Thematic focus overview

This section gives an overview on the thematic focus of research in Hybrid Renewable Energy Systems (HRES) in the last decade, period 2005 - 2015. Those many different focus goes from technical and economic, to environmental, regulatory or political.

This section provides an overview of the multiple aspects beyond the techno-economic approach of the system design, while the next chapter 4 is focusing more in depth in technical and economic criteria analysis.

This analysis also provides insights of the latest trends in research regarding: financing and business models, system integration, education, policy and regulation, and geopolitics of HRES for a more detailed overview in chapter 5. After this thematic focus analysis, an integrated value chain for HRES systems is proposed, also in chapter 5, identifying primary and support activities.

3.4.1 Thematic focus evolving beyond techno-economics

The thematic focus of research publications are widely related to technical aspects, with some economic approaches but very little environmental focus. As displayed in figure 3.20 it also integrates very different aspects that go from policy or education to energy access and sustainable development.

Technical focus is devoted to almost half of the publications, 126 out of 265 (46%) as shown in figure 3.20. Those innovations in HRES have the following technical focus: location (3), design modelling (20), sizing (50), operation/ control (27). Economic focus is also widely present, as in 56 publications (21%), regarding: value chain (3), economic or costs (42) and financing, business modelling and energy markets (11).

Environmental focus is hardly present, via 18 publications (7%). The environmental focus so far is present with 3 different approaches: CO2 emissions (11), tax on carbon emission (3) and Life Cycle Assessment (LCA) (4). The few inter-disciplinarity research identified in energy engineering might be one cause as well as the lack of political commitment from government and society that don't accelerate the implementation of economic binding mechanisms, e.g. carbon trade markets.

Other aspects that are highly present in the publications of innovations in HRES, with 68 publication or 26%, are as broad as: education (3), policy (17), sustainable development (29), and energy access (19).

The evolution of the thematic focus over recent years, displayed in figure 3.21, shows an increasing interest of the research community for focusing on

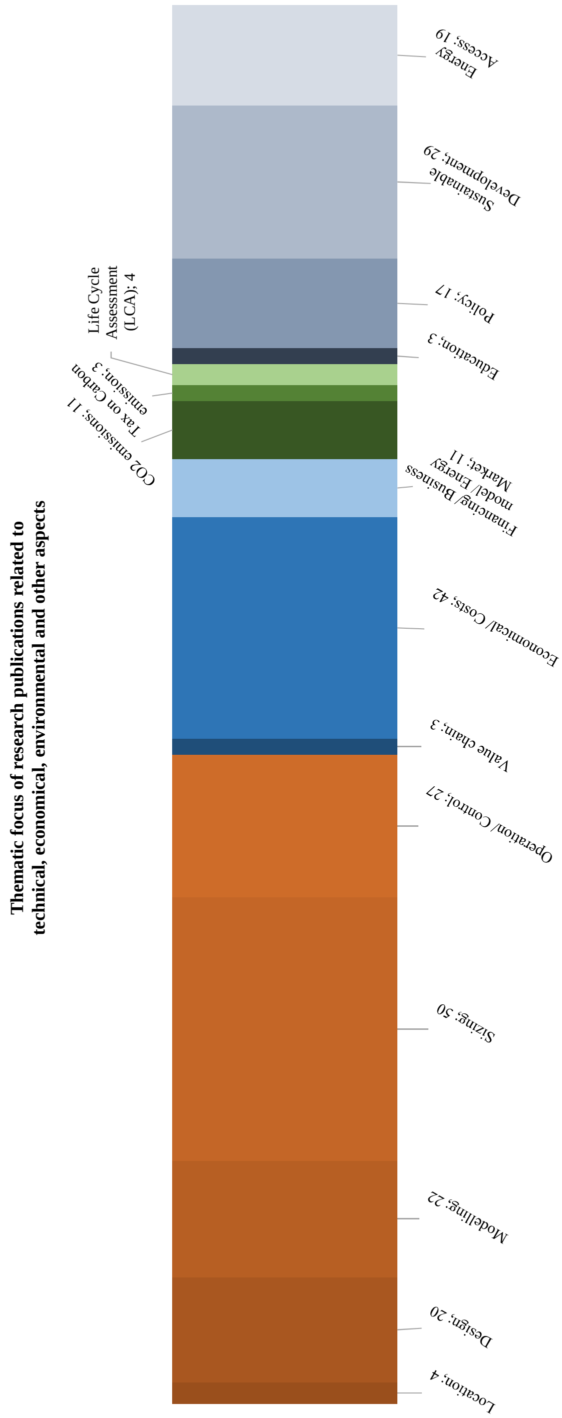


Figure 3.20: Thematic focus of research publications related to technical, economic, environmental and other aspects (total 265 publications)

broader thematics than the classical system design of HRES. Figure 3.22 includes the table detailing the number of research publications per thematic focus and per year, during the period 2005-2015.

Policy and regulatory aspects as well as energy access and sustainable development have been more popular since 2012. Whether the global market situation following the financial crisis after 2009 or the launching in 2011 of the initiative "Sustainable Energy for All" by the United Nations [3] influencing this growing focus is uncertain, but the enlargement beyond the techno-economic research focus is a trend.

3.4.2 System design focused in techno-economic

System design is currently mainly devoted to the technical and economic areas. An overview of the current thematic focus in techno-economic areas is going to be provided in this chapter. A more in depth analysis of the latest innovations in those research areas of HRES is delivered in the next chapter devoted entirely to system design.

System design: Location and Demand

The location of HRES systems is under represented in scientific publications although the renewable energy potential is directly dependant on it. The energy potential of Renewable Energy Systems (RES) is not generally studied with System design activities. Main reason identified is that in many of the systems studied there is a pre-existing load powered by a diesel generator. The hybridization of those systems with renewable sources of energy is an opportunity to reduce the dependence from fuel and increase the environmental sustainability of the system. For this reason, in many cases there is not enough of one of the renewable sources studied since the location is defined by the existing load (not being previously optimized).

System design: Technical design

The technical design phase look at the decisions to be made (or the taken choices by default configurations) regarding the elements or building blocks that configure the hybrid renewable energy system (HRES). Those choices or decisions are on some occasions evaluated with the discussion of scenarios considering key variables, listed below, or tested in experimental setups or pilot facilities.

Within the literature six main aspects have been identified as elements or building blocks of the decision process that lead to the design of a HRES:

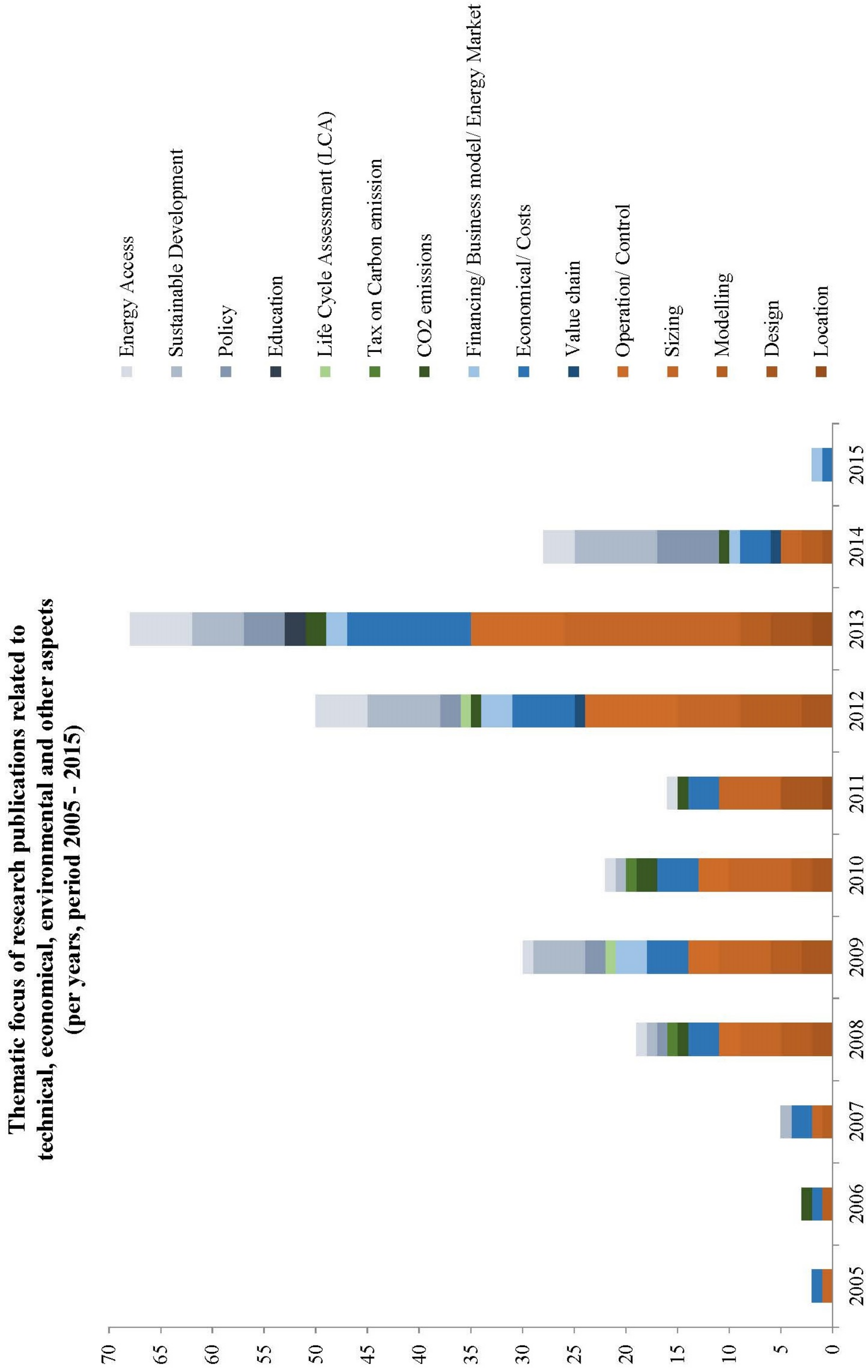
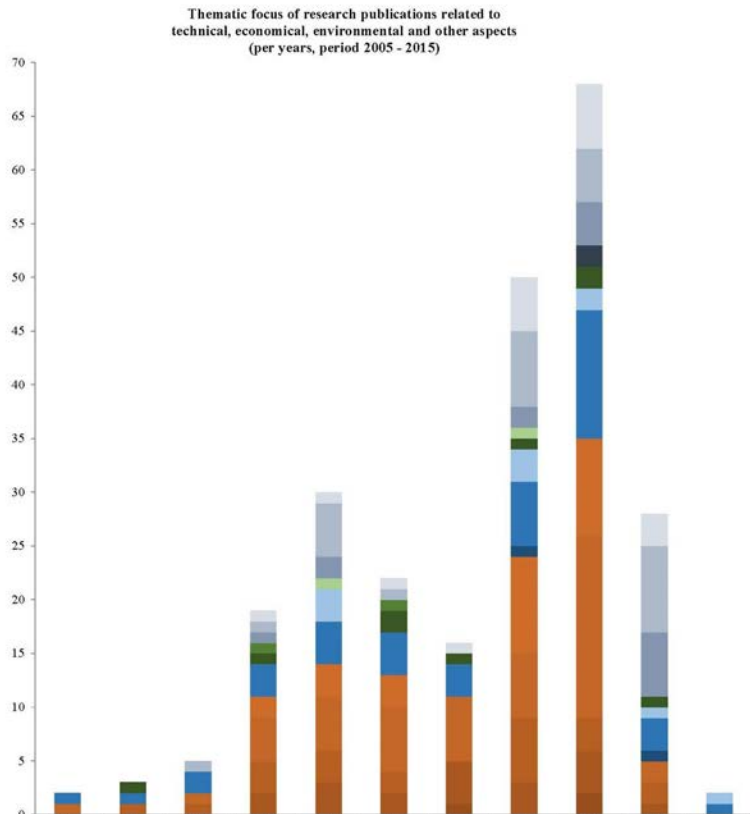


Figure 3.21: Thematic focus of research publications related to technical, economic, environmental and other aspects (per years, period 2005 - 2015) (total 265 publications)



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Energy Access				1	1	1	1	5	6	3	
Sustainable Development			1	1	5	1		7	5	8	
Policy				1	2			2	4	6	
Education									2		
Life Cycle Assessment (LCA)					1			1			
Tax on Carbon emission				1		1					
CO2 emissions		1		1		2	1	1	2	1	
Financing/ Business model/ Energy Market					3			3	2	1	1
Economical/ Costs	1	1	2	3	4	4	3	6	12	3	1
Value chain								1		1	
Operation/ Control				2	3	3		9	9		
Sizing	1		1	4	5	6	6	6	17	2	
Modelling		1	1	3	3	2		6	3	2	
Design				2	3	2	4	3	4	1	
Location							1		2		

Figure 3.22: Thematic focus of research publications related to technical, economic, environmental and other aspects (per years, period 2005 - 2015) (total 265 publications)

1. Availability of renewable energy sources (RES).

2. Type of generation technologies available, in relation to the RES available or to the type of application/load.

3. Coupling configuration of AC/ DC elements: generation, consumption, conversion (inverters, converters) and storage or back-up systems.

4. Possibility or convenience of a back-up system, storage element or grid connection.

5. Expected efficiency increase by a controller/ optimization of the management system or the installation of a tracking mechanism to maximize the energy input from renewable resources.

6. Other non-technical aspects considered in the design goes from power supply reliability or economic impact in the cost of energy, to aesthetics, noise or maintenance forecasts, and carbon emission savings.

System design: Modelling

Modelling is the phase where real energy systems are approximated to a model, defined with a time resolution (typically 1 hour for HRES), that is based on specific inputs and mathematical equations. Software implementation gives key expected outputs of the system. The modelling usually happens after the design choices and the outputs provided by the model facilitate forecasting the power generated by the renewable sources and conventional generation and facilitate insights on the expected operational behaviour of other system components such as storage (batteries) or back-up systems (diesel genset).

System design: Sizing

The size of the studied Hybrid Renewable Energy Systems (HRES) are mostly defined by the installed capacity of the generation energy sources separately quantified in kW (23 out of 33 articles in the table 4.2), few of them mention the total capacity of the system as a whole (6 out of 33), few others define the maximum generation capacity as in kWp (3 out of 33), and finally only one was found being defined by the surface in m^2 of the renewable generation sources.

From around 1 kW to 30 kW of each renewable energy generation technology is the range of installed capacity of most of the sized hybrid systems studied (26 out of 33 in the table 4.2) in the next chapter. It is described also in the following chapter the most relevant insights from the reviewed articles that are organized according to the total size of the generation technologies or the system as a whole within the following intervals:

- 1 kW - 10 kW - 30 kW - 1 MW - + 1 MW

System design: Operation and Control

Operation and Control is the only aspect identified in relation to the Supply chain activities. As introduced previously, a more in depth analysis of the latest innovations in those research areas of HRES is delivered in the next chapter devoted entirely to system design including operation and control. Other activities related to market viability, implementation and life cycle follow-up of HRES systems do not yield significant work from researchers.

3.5 Conclusions after scanning nearly 400 innovations in HRES

An overview on the thematic focus of research in Hybrid Renewable Energy Systems (HRES) in the last decade, period 2005 - 2015, is provided. This review covers multiple key aspects of HRES such as: the main focus of the research (technical, economic, environmental, geopolitical,etc.); the design of the system (type of load, energy sources, storage, availability of meteorology data,etc); different optimization criteria and objective function; software tools; and the type of application and country.

A methodology for searching, identifying and categorizing innovations related to HRES is proposed. Applying this methodology during this PhD work results in a primary database with a categorized bibliography including almost 400 entries.

Research and innovation opportunities in multi-disciplinary thematic areas has been identified. The analysis of innovations regarding the system design for Hybrid Renewable Energy Systems (HRES) have identified untapped potential for research community. Currently system design is mainly technical driven by economic analysis regarding return on investment. More research regarding viable business models will be needed. As for environmental aspects, the beneficial impacts of renewable energy are hardly introduced as an economic value that is so far the most important decision-making criteria. The need for affordable tools for decision-making integrating technical, economic and environmental aspects would ease the roll-out of HRES.

Those identified opportunity areas for future innovations would have many benefits, including: more integration of real-life cases in research works, a multi-disciplinary approach to develop innovative business models and other enabling areas, and introducing the environmental benefits in the decision making to encourage more investments.

Chapter 4

Design of stand-alone HRES beyond economic optimization

There is a current trend [92] of developing multi-objective sizing methodologies to become reliable, feasible and/or environmentally friendly for hybrid renewable energy systems.

Hybrid systems with two types of Renewable Energy Source (RES) plus an auxiliary source of energy lead to a minimization of energy costs and an increase in reliability, while not increasing the size of the generation units [92]. [92] also points out that sizing methodologies based on averages or worst scenarios leading to the over-sizing of system components.

Beyond the importance of the price of energy, [93] highlights that promoting design mechanisms have the potential to lower costs. Moreover, it is also crucial aside from the energy price, to have legislative and socio-political support.

There is a growing scientific interest for off-grid systems [91] where, beyond the cost of energy, there are increasing potential benefits for sustainability and local development. For the case studies using HOMER, based on the total Net Present Cost (NPC), [94] show that this NPC criteria has a high sensitivity analysis of outputs in relation to changes in inputs.

Taking into account those motivations and trends above, a wide analysis of design criteria is proposed in this chapter.

4.1 Overview design criteria

Following the analysis of energy situation and policies in Africa in the light of the Energy Indicators for Sustainable Development (EISD) [80], it is highlighted the need for the integration of different dimensions via joint cooperation of technical scientists and policy makers. The EISD framework covers three major dimensions: social (4), economic (16) and environmental (10).

Another proposal is defining a criteria framework with different sustainability dimensions as: environmental, economic, social, technical and institutional, proposed by [95] after studying pico-PV for electric light systems.

As for design and simulation software, HOMER and iHOGa are the more popular programmes for simulation and optimization of HRES [93].

4.2 Economic optimization

The most common economic criteria are: Net Present Cost (NPC) and Levelized Cost of Energy (COE)[92].

The three most common applications for the introduction of renewable energy off-grid are: telecommunication stations, households and villages are using comparable economic criteria. The most frequent economic criteria that enables comparison between different installations is Levelized Cost of Energy (in USD/kWh), found under the acronyms of COE or LCE or LCOE. This COE is the criteria used by HOMER as the most widely system configuration software being used.

In addition to economic criteria, reliability criteria is having a relevant impact on the economic analysis of those systems. As for the reliability criteria introduced in combination with economic, we can find the following ones:

- State of Charge (SOC)[22];
- Loss of Power Supply Probability (LPSP) [96] and Loss of Load Probability (LLP) [23];
- Days of energy autonomy [56] [34].

Other economic criteria occasionally identified are: Local Marginal Prices (LMP) [97], Net Present Value (NPV) [32] and Total Cost (TC) [69] also found in literature as Total Cost of Ownership (TCO).

Economic criteria for top 3 applications The three most popular applications for the introduction of renewable energy off-grid are:

- telecommunication stations
- households
- villages

For each of the three most popular applications identified in the primary database, the most relevant system information, e.g. size and hybrid configuration, and the key economic criteria is detailed below.

Systems from 1,5 kW to 2 kW for telecom applications are:

- estimated 0,73 USD/kWh for a 1,5 kW PV/ Wind/ Battery system with an Annualized Cost of the System (ACS) of 9.708 USD, with a LPSP minor to 2 % and 25 years lifetime in China [96].
- estimated 0,16 USD/kWh for a 3,5 kW max capacity (1,5 kW average) PV/ Wind/ Battery system with a Total Cost of the system of 37.033,9 USD with a LLP minor to 0,045 and an autonomy from 0,9 to 0,845 with 20 years lifetime in Turkey [23]. The cost of auxiliary energy is 0,5 USD/kWH, triple than the cost of energy of the system.
- 0,44 USD/kWh for a 2 kW telecom tower with a PV/ Diesel/ Battery system with a renewable fraction of 47% and 100% reliability for a lifetime of 20 years in Spain, case study in chapter 1.

The power demand of a typical telecom tower in India is in ranges from 1 kw to 8,5 kW, where 80% of the configurations demand less than 3,5 kW, according to [98].

Systems from 1,45 kW to 15 kW for households are:

- 1,29 USD/kWh for a 1,45 kW PV/ Wind system with SOC major than 80% for the summer period (1,87 USD/kWh with UPS) in Corsica island [22].
- 0,49 €/kWh for a 2,8 kWh/day PV/ Battery system with 1,7 days of autonomy with a NPC of 15.233 €[56]. This author shares that the COE for Diesel/ Battery systems is greater than 1 €/kWh.
- 11.871 USD of Total Cost for a 3,6 kW Wind/ FC/ Battery system in Spain [69];
- 1,04 USD/kWh for a 7,5 kW Wind/ PV/ Battery with a NPC of 53.296 USD (using HOMER) in China [38].
- 0,71 €/kWh for an overall of 12 kW PV/ HP system with Net Present Value (NPV) of 75.200 €with 37% PV penetration for 20 years operational life span in Denmark [87].

- from 0,47 to 0,80 €/kWh for a 15 kW Wind/ Diesel/ Battery system with a renewable fraction (REF) higher than 45% for 20 years lifetime in Greece [49].

Systems from 35 to 300 kW, and few MWs, for villages or remote communities are:

- 0,42 USD/kWh (0,44 USD/kWh grid power price)) for a 35 kW PV/ Hydro/Biodiesel/ Battery system with a total Net Present Cost (NPC) of 673.147 USD (using HOMER) and a lifetime of 25 years in India [30].

- 0,28 USD/kWh for a 65 kW PV/ micro Turbine/ Battery system (0,33 USD/kWh with Diesel generator as back-up) with 0,3 to 1,0 days of autonomy in Palestina [34].

- 0,19 USD/kWh for a 300 kW Wind/ PV/ Battery/ Grid with a total Net Present Cost (NPC) of 3.157.639 USD/kWh (using HOMER) using 56% renewable energy in Romania [57].

- 0,17 USD/kWh for a 7 MW PV/ Diesel/ Battery system (with 2,5 MW PV and 4,5 MW Diesel) with 27% PV penetration and a lifetime of 25 years in Saudi Arabia [99].

Other applications as for street lighting systems have a COE of 1,08 €/kWh for a 60 W street light PV/ Battery/ Fuel cell/ Hydrogen system and 25 years lifetime [52].

According to this information, the cost trend for micro-grids and off-grid systems are not strongly declining despite more competitiveness and cost reduction of renewable energy technologies. This is illustrated in the evolution of cost per years per application, visualized in figure 4.1, and for different sizes in figure 4.2. [100] shows that the main divers of competitiveness for micro-grid systems is due to the higher power prices and unreliable grids, more than on declining micro-grids costs.

4.3 Technical system Design

4.3.1 Location and Demand

The location of HRES systems is under represented in scientific publications although the renewable energy potential is directly dependant on it. The

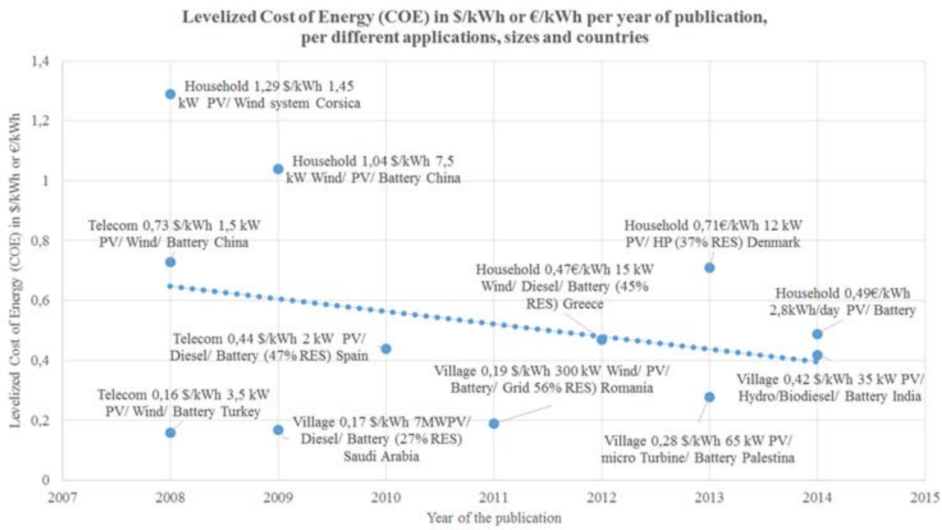


Figure 4.1: Levelized Cost of Energy (COE) in USD/kWh or €/kWh per year of publication, per different applications, sizes and countries)

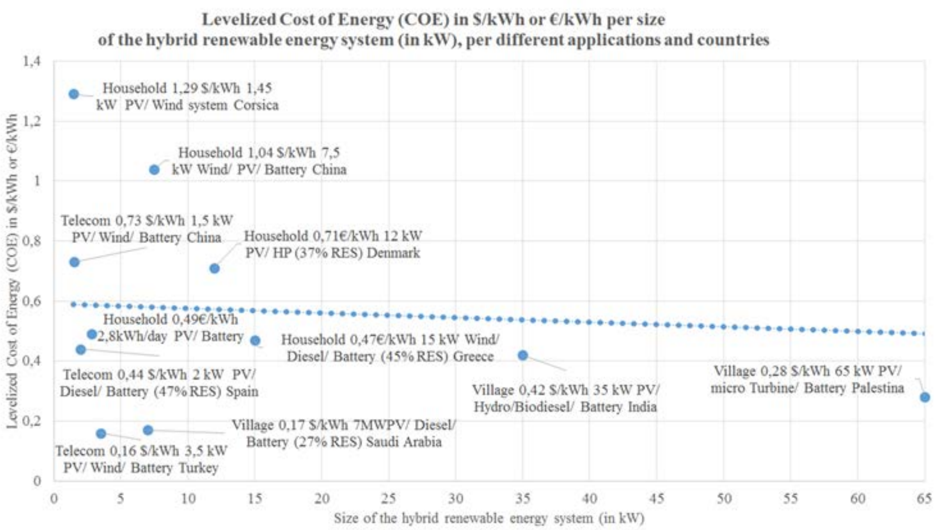


Figure 4.2: Levelized Cost of Energy (COE) in USD/kWh or €/kWh per size of the hybrid renewable energy system (in kW), per different applications and countries)

energy potential of Renewable Energy Systems (RES) is not generally studied with System design activities. It is clear from the case studies in Tunisia [14] and in Corsica Island [15] that an optimal location of the systems is key for the future potential of energy production with renewable energy:

- [14] develops an optimization procedure that identifies the best locations to install an hybrid photovoltaic/wind system based on the renewable energy potential of the territory, solar radiation distribution and global wind speed. For the case study in Tunisia the protocol evaluates and identifies the 5 best locations for solar/wind power plants from 38 to 182 MW over 30 years period. It does not take into account aspects of grid interconnections or the competition with fossil fuels that after the location would influence the decision making for the power plants installation.
- [15] discusses the renewable energy potential of 5 sites in the Island of Corsica located in the Mediterranean sea and define 2 of them as best locations for an hybrid PV/Wind/battery system of 2 to 4 kW size. This case study highlights the relevance of the placement and availability of renewable energy before sizing and adds to the discussion the importance of the complementarity between solar and wind energy in hybrid systems.

Where there is more extensive research is in the location of RES-based Distributed Generation (DG) in power systems, where the grid parameters are taken into account more than the renewable energy potential. [101] provides a review of the optimization methods for the placement of Distributed Renewable Generation (DRG)in power systems and shows the increasing relevance of planning and location from the number of publications in the last several years. This line of research could benefit location research for off-grid hybrid systems and provide more relevance to the optimal location in the design of HRES.

4.3.2 Technical system design: Technical design

The technical design phase is about the decisions to be made and default configurations regarding the elements or building blocks that configure the hybrid renewable energy system (HRES). Those choices or decisions are in some occasions evaluated with the discussion of scenarios considering key variables, listed below, or tested in experimental setups or pilot facilities.

Within the literature, six main aspects have been identified as elements or building blocks of the decision process that lead to the design of a HRES:

1. Availability of renewable energy sources (RES) [37] [68] and the availability of weather data [52][58], and in what time resolution (typically 1h)[40][102]. Mainly regarding solar and wind, this is also called a pre-feasibility study [26].

- [37] highlights that the high availability of renewable sources is key. As an example, the similar cost of a PV-Wind hybrid and a PV-only system, around 0,5% difference, makes the second one a better option due to the high solar potential versus a low wind potential in Nicosia, Cyprus.

- [68] provides a guide to choose the optimal energy mix of renewable sources to supply electric and thermal energy for consumers, with a study case in a tourist resort in Romania.

- [52] a simple model is designed to run simulations using real weather data. The model of the system integrates: PV modelled by a gain converting weather data into electrical power, battery composed of an integrator and a gain, Fuel Cell reduced to a gain that provides the equivalent chemical power, and load as a constant power. This model is simulated using SIMPLORER software and weather data collected in 2013 in the city of Geneva (Switzerland) with a 5 minutes sample. This design could be applied to more complex hybrid systems and be further developed using real data for the load profiles, wind speed, etc.

- [58] implements both simulation and physical models for the design of an hybrid solar-fuel cell power plant for a telecommunications system in Poland.The design includes models from a PV array, a simple PEMFC, power electronics converters and control units, and it was built on Simulink software. The inputs for the simulations have been the solar irradiation and ambient temperature to obtain as outputs the load power and current and source's current. The experiment set up was composed by a GPV 110 ME solar panel, NP 50 PEM fuel cell and power converters.

- [40] combines a Wind Turbine (WT) with a solar PV array for an off-grid water pumping system, analysing the optimum PV arrays size for a maximum pump efficiency via an experimental set up conducted in Texas, USA. The installation of a 90 W WT and three different PV array, of 320, 480 and 640 W each, was operated for 11 months, from the period of October 2010 to August 2011, with an extensive data collection (1 minute time period) of the relevant weather conditions, the renewable energy generation and the water pump performance. The results of the statistical analysis of the data of the tests provided the 640 W to be the most efficient hybridization off-grid for a 900 W WT, with a 55% average peak efficiency for water pumping.

- [102] proposes an optimization methodology that instead of using meteorological data with 1-hour time resolution, typical conventional PV plant design procedures, is capable of using high time resolution as of 1-minute. The results differ for the LCOE in Euro/MWh from 2,7% to 2,8%, for the total energy produced in MW from 1,9% to 3,1%, and for the total cost of the plan in million Euros from 4,6% to 5,9% what would be translated in significant savings for the PV plant implementation and operation.
- [26] points to the need of a pre-feasibility study to analyse the availability of renewable energy sources at a particular site based on weather data and defines the design of the hybrid system configuration to be later sized and optimized.

2. Type of generation technologies available [72], in relation to the RES available [15] or to the type of application/load.

- [72] reviews the types of solar energy systems available for agricultural applications in Malaysia: solar photovoltaic, solar thermal for pumping water, drying crops, cooling the storage areas and producing heating/cooling for households. Both solar photovoltaic and solar thermal are the most suitable for agricultural applications, especially in remote areas. The design of hybrid systems should consider the available solar technologies in the design.
- [15] similar to the pre-feasibility study approaches, makes clear that a study of the renewable energy potential is paramount before the implementation of a renewable energy system. It also shows that the choice of system configuration affects the SOC (State of Charge) profile, especially at low wind potential sites.

3. Coupling configuration of AC/ DC elements [22][20]: generation, consumption, conversion (inverters, converters) and storage or back-up systems.

- [22] studies two system configurations in the design of an hybrid PV/Wind power system: whether to connect the wind turbine to the load via an AC/DC converter and a DC/AC inverter, or whether to connect them directly to AC via a UPS (Interruptible Power Supply) and the energy surplus of the wind turbine transformed in DC and stored in the batteries.

- [20] provides an overview for two basic designs of hybrid system topology such as: DC-coupled system or AC-coupled system.

4. Possibility or convenience of a back-up system [22], storage element [21] [28] or grid connection [58][103].

- [22] shows the impact of the design with the UPS to a larger sizing and the optimization criteria resulting in a higher SOC (State of Charge) and an increased LCE (Levelized Cost of Energy), specially for high wind potential regions.
- [21] the relevance of introducing a storage system in the design of a renewable system in stand-alone to provide a continuous output power and suppress the fluctuations by renewable sources that affect the system frequency. For a stand-alone renewable system a fuel cell is included in the design and simulation results show that it is controlled to supply deficit power between the load and the hybrid solar photovoltaic and wind turbine.
- [28] designs an hybrid system introducing solar and hydro storage to an hydroelectric power plant (HEP) in Croatia. While the current HEP of 1,9 MW has no upper-reservoir, the installation of a 12 GW PV plant and a storage pool of 28.000 m3 would enable the use of almost all energy to operate the HEP.
- Whereas both simulation and field tests at [58] were very good, the challenging aspect would be the integration of the system into an existing network, that could be enabled via a proposed DC-micro grid.
- [103] considers in the design the critical or break-even distance for a cost-effective decentralized renewable energy system over a grid connection. Between 43,8 km and a negative distance is the break-even distance, depending on the considered component costs. This critical distance means the cost of energy is from 7 times to less than half of the cost of conventional energy in this case of a 25 kW hydrogen powered system for a rural healthcare center in India.

5. Expected efficiency increase [10] by a controller/ optimization of the management system or the installation of a tracking mechanism [38] to maximize the energy input from renewable resources.

- [10] highlights the key role in the efficiency of stand-alone PV systems of the design parameters as: solar size, battery bank, charging controller, angle of inclination or tracking system, among others. The system design is key to avoid over- or under-sizing and to have an adequate, reliable and affordable stand-alone PV system.

- [38] states that there are several design conditions that are litle studied such as the PV module tilt angle, the effect of ambient temperatures or the load variations of hybrid Wind/PV/battery systems in comparison with PV/battery or Wind/battery systems. In this study the maximum of solar power generated would be 5,15% higher with a solar tracking system than a system with an optimized PV module angle of 45 degrees for PV arrays facing south, 8325 kWh/year versus 7916 kWh/year for a household type of load in Urumqi in China.

6. Other non-technical aspects considered in the design range from power supply reliability [44] and economic impact in the cost of energy, to aesthetics, noise and maintenance forecast [37], and carbon emission savings [99].

- [44] focus on the complexity of the design, control and optimization of hybrid stand-alone systems than the ones with only one source of energy. The power supply reliability for different weather conditions and the system cost are two major concerns in the design.

- [37] highlights other benefits from not including wind in the design for a household application as: avoiding noise from the operation of the wind turbine, the aesthetic integration in the building and the maintenance costs, that have not been quantified in the comparison.

- [99] compares the design of a PV/Diesel hybrid system and a PV/Battery with the PV-only case. It turns out that with a 27% of PV penetration the carbon emission savings are about 17% and having a battery system with 60 minutes of autonomy decreases the cost of energy (COE) around 15%.

4.3.3 Technical system design: Modelling

Modelling is the phase where real energy systems are approximated to a model, defined with a time resolution (typically 1 hour for HRES), that based on specific inputs and mathematical equations and software implementation gives key expected outputs of the system. The modelling is happening usually after the design choices and the outputs provided by the model facilitate forecasting the power generated by the renewable sources and conventional generation and facilitate insights about the expected operational behaviour of other system components as storage (batteries) or back-up systems (diesel genset). This section of modelling focuses on the power system from the technical point of view and the economic modelling or the objective function modelling are studied in later chapters.

- A. Inputs for the Modelling. There are four main inputs identified as required for the models:
  - A.1 Location. The location is the main factor that defines weather conditions and the potential availability of renewable energy sources.
  - A.2 Weather data. Models can also integrate directly, without defining the location, the weather data that is mainly: solar radiation with the influence of temperature, and the wind profiles with the effect of local air density.
  - A.3 Manufacturer data or typical values of system technologies. The commercial information provided by manufacturers or typical values that characterize the generation and storage technologies are: solar PV panel, wind turbine, diesel and battery.
  - A.4 Load profile or energy demand. The characterization of the demand for the power system is also required as input for the modelling.
- B. Modelling strategies. The model definition can be described using mathematical models, detailed equations and specific parameters or it can be also defined using a model offered by well known software tools as HOMER or MATLAB/Simulink. As identified in the following twenty references describing different modelling strategies, [96][26][22][97][6] [67] [87][52][104][84] [41][50][33] [68][39][17][18][13][42][48], the generation systems considered mainly are solar PV (PV) and wind turbines (WT), and as for storage or back-up systems are batteries (Battery) or diesel gensets (Diesel). As it can be more easily indentified in the summary table others models include more than the previ-

References	PV	WT	Battery	Diesel	Others
[96]	x	x	x	-	Objective function
[26]	x	x	-	x	
[22]	x	x	x	-	Inverters
[97]	-	-	x	-	Converters
[6]	x	-	x	-	
[67]	-	-	-	-	Energy hubs
[87]	x	-	-	-	Solar technologies
[52]	x	-	x	-	Fuel cell
[104]	x	-	-	-	
[84]	x	x	-	x	
[41]	x	x	x	x	Fuel cell
[50]	-	-	x	x	Inverters
[33]	x	x	x	-	Fuel cell
[68]	-	x	-	-	
[39]	x	x	x	-	Inverters
[17]	x	x	-	-	
[18]	x	x	-	-	Fuel cell
[13]	x	-	x	-	
[42]	x	x	-	-	
[48]	x	x	-	x	
Total 20 articles	16	11	8	5	12

Table 4.1: Modelling of the HRES defined by the generation systems considered, mainly solar PV (PV) and wind turbines (WT), and as for storage or back-up systems, with batteries (Battery) or diesel gensets (Diesel), among others.

ous technology aspects mentioned, among others: fuel cells,inverters, energy hubs or objective functions.

[96] models a PV system based on three components: a PV array power model, the solar radiation on the PV module surface and the PV module temperature model. As for the Wind turbine system model, it depends on three elements: the power output curve of a chosen wind turbine, the wind speed distribution of a selected site and the tower height. As for the battery model, it integrate three characteristics: the battery state of charge (SOC), the terminal voltage and the battery lifetime. It also models the objective functions for LPSP and ACS.

[26] models the photovoltaic system based on the solar cell and the photovoltaic module, the wind energy system based on the wind dynamics and the generator modelling, and the diesel generator based on the rated capacity of the generator that is equivalent to the maximum load.

[22] bases the PV power generation simulation model in two key elements: the solar radiation on the PV module surface and the PV generator mode. As for the solar radiation, the horizontal solar radiation data is converted into tilted solar global radiation. To estimate the PV generator output, it considers the solar radiation available on surface, the ambient temperature and the manufacturer data for the PV module. For the modelling of the wind turbine system model, it proposes a quadratic equation taking as inputs: the rated power, the cut-in wind speed, the rated wind speed and the cut-off wind speed, where the wind profile is adjusted for height. Then for the battery model it takes into account the maximum and minimum allowable storage capacities, the temperature and the nominal capacity of the battery. Finally, for modelling the inverter mode it takes into account the inverter nominal power and the efficiencies at 10% and 100%, defining the inverter equation.

[97] is modelling the converter with its conversion efficiency taking into account the ratio of steady state power output and the input power of the converter. The storage is modelled considering time as additional variable and determining the energy content by an integral function of the terminal power.

[6] proposes the modelling of photovoltaic cell with the typical I-V characteristic of a PV array depending on: the PV array output current, the PV array output voltage, the number of cells connected in series, the number of modules connected in parallel, the charge of an electron, the Boltzmann constant, the pn junction ideality factor, the cell reverse saturation current and the cell temperature.

[67] models energy hubs, converters with multi-inputs and multi-outputs, and storage elements. After modelling those elements, a robust optimal scheduling is performed for an energy hub.

[87] defines the electricity supplied by the PV module based on: the hourly global irradiance for the angle of the inclined surface, the installed area of the PV module and the PV efficiency that is assumed to be constant. It also models other solar generation technologies as: a solar thermal collector, a heat pump, as well as a back up system working independent from weather conditions.

[52] is modelling a photovoltaic generator with a gain converting solar insolation into technical power, where the gain is the multiplication of the PV area in square meters per the PV efficiency. The solar insola-

tion is obtained from the horizontal direct and diffuse irradiation and the inclined surface. The model of the battery is built up as an integrator and a gain to compute the stored energy. The fuel cell is modelled as a gain from the chemical power from hydrogen (H2),considering supply of constant power and constant efficiency.

[104] is modelling and analyzing hybrid photovoltaic-thermal collectors (PV/T), describing the performances of photovoltaic-thermal air collectors and photovoltaic-thermal water collectors, and studying applications as building integrated (BIPV/T).

[84] proposes the mean monthly RES power production as an equation integrating the solar power factor and the wind power factor, each multiplying the total rated power of the generation system and the sum multiplied by the efficiency of the transportation from batteries (set up to 90%). The solar power factor is obtained via equations with inputs as: monthly average of daily solar radiation power density, the daily time period (related to the geographical latitude), the efficiency of the solar panel, the monthly average daily temperature, among others. The wind power factor equations integrates: the wind turbine power curve, the wind velocity and the monthly probability density function. The mean monthly diesel production takes into account the mean monthly power demand minus the mean monthly RES power production. Then the fuel consumption equation integrates the consumed fuel thermal capacity, the diesel genset mean annual efficiency and the energy transportation total efficiency.

[41] models the output power of a wind turbine based on the power curve (manufacturer), the height and the roughness of the land surface. This output power of the PV panel is calculated as a function of the horizontal solar irradiation, the longitude/latitude of the location, the inclination of the panel, the temperature effect and the PV array characteristics. The fuel cell electrolyzer and the hydrogen tanks are also modelled. The battery is modelled with HOMER software. The diesel generator is modelled to obtain the fuel consumption as a function of the output power, taking as inputs: the fuel consumption curve coefficients (manufacturer) and the nominal output power of the diesel generator.

[50] proposes a model for the lead acid battery bank including quite complex formulation considering: charging capacity, current operation, temperature effects, etc. The inverter is modelled by its efficiency and

takes into account the load in the AC bus, the rated power of the inverter and two parameters provided by the manufacturer (typical values). The efficiency of the inverters drops dramatically if the load is less than 10% of their rated power. The diesel generator model obtains the fuel consumption as a typical function using as inputs the rated power, the power generated and manufacturer parameters.

[33] considers the PV power production out of the solar radiation and the load current. For this the PV power production takes as inputs the replication of the installation, the tilt angle of the arrays, the ambient temperature and a coefficient related to the mean wind speed. The technical specifications of a commercial micro wind turbine are considered taking into account the wind resource power estimated by the Weibull model for frequency distribution function defined after real data gathering via anemometers and electrical sensors. Fuels cells are also modelled. Both the battery bank technical characteristics and the load profile are known.

[68] proposes the output and the revenue functions for a wind turbine. For the output function of a wind turbine there is a logistic model simulating a function of the output power and the wind speed with two coefficients and one scale factor. The revenue function of the wind turbine is proposed as a function of: the starting and ending time, the price of electricity power per unit of time, the operation/maintenance cost of a wind turbine per unit of time and the wind speed estimated as a Weibull distribution.

[39] PV power module is a function of the current-voltage equations including parameters such as: short circuit current at normal conditions (25°C, 1kW/m2), the open circuit voltage temperature coefficient, where commercial specifications are provided by the PV manufacturer in data sheets. This modelling proposes an output power wind generation as a function of the wind speed and the power-speed curve at the installed site, where the manufacturer characteristics provided are: hub height, output frequency, output voltage, rated output power, cut-in and cut-off wind speed and the power law exponent (1/7 for open land). The battery is modelled as a voltage source in a kinetic model that is a function of the state of charge in series with an internal resistor, also including temperature dependence, self-discharge rate and charge-discharge efficiency. The inverter is modelled based on its efficiency.

[17] defines the PV modules from the PV cells modelling based upon data sheets from the manufacturers with current-voltage for 3 conditions: short circuit, open circuit, maximum power for reference temperature of 25°C and solar irradiation of 1.000 w/m2. The wind turbine power is a function of the area swept out by the rotor, the air density, and the cubic power of the wind speed taking into account that technical characteristics are provided by the manufacturer.

[18] the PV array model includes the efficiency of the DC/DC converter (approx. 90-95%). The PV manufacturer data is: the current and voltage at the maximum power point, value of current at short circuit current conditions, value voltage at open voltage conditions, temperature coefficient at short circuit and open voltage conditions and the number of solar cells. The wind generator model is proportional to the cube of the wind speed with equations including the efficiency of the AC/DC inverter (approx. 90-95%). An electrolyzer and fuel cell are also modelled and it includes power management strategies.

[13] proposes a simple modelling of a PV panel as a function of the solar irradiation, the current characteristics, the rated capacity and a PV setting factor. The battery modelling includes the battery bank lifetime, the battery wear cost and it's marginal cost of energy. The rest of the elements of the system are modelled using HOMER software.

[42] is adopting a mathematical modelling for the solar potential as a function of the global irradiation, the diffuse irradiation, the incidence angle and others. Then the PV module is represented as s function of the I-V characteristic, the solar irradiation and the temperature). The potential wind energy is modelled with a Weibull distribution. The wind turbine is simplified as a function of the probability density of Weibull and the manufacturer characteristics.

[48] estimates the wind power output as a function of the wind velocity, a factor to account for air density, a power coefficient, the wind turbine rotor swept area, the wind turbine and generator efficiency from manufacturer data. The solar array is modelled with a solar PV array that depends on the conversion efficiency, operating voltage, operating current, number of parallel and series solar cells. The diesel generator fuel consumption is calculated as a quadratic expression of the rated power (light load working conditions) with coefficients provided by the manufacturer.

- C. Time resolution for the Modelling. For HRES tipically 1 hour is the time resolution for modelling. [25] studies the influence of temporal resolution and the efficiency if the standard 1 hour time step in the modelling of renewable power systems is smaller. As a result of a 1 second time step the energy output is increased from 4,3% (for a wind speed below the rated wind speed) to 7,0%. Moreover, the fuel consumption for a 1 hour time step is 5,6% lower than for a 1 second step due to the large number of start/stop cycles and partial loading. A time step of 1 second for a diesel generator would be very disadvantageous from the point of view of control: increasing the cost of fuel, reducing the life time, increasing the frequency fluctuation and reducing the power quality. Overall, the influence of the temporal resolution for modelling is dependent on the configuration of the system, while a PV/Battery would be unaffected the highest impact would be especially in the systems with only diesel as back-up.

- D. Outputs after the Modelling. Key outputs forecasted after the modelling are the power generated by the renewable energy sources (kWh of solar energy, kWh of wind energy, % of renewable fraction) or the conventional generation (kWh diesel, litres of fuel consumed). Another output is the operational behaviour of other system components as storage in batteries (% state of charge).

  The influence of key parameters is also studied, as in [41] where the output power of the PV panel can have a variation of up to 10% depending on the solar position and the panel tilt angle.

4.3.4 Technical system design: Sizing

The size of the studied Hybrid Renewable Energy Systems (HRES) are mostly defined by the installed capacity of the generation energy sources separately quantified in kW (23 out of 33 articles in the table 4.2). Few of them mention the total capacity of the system as a whole (6 out of 33), few others define the maximum generation capacity as in kWp (3 out of 33), and finally only one was found to be defined by the surface in m^2 of the renewable generation sources.

From around 1 kW to 30 kW of each renewable energy generation technology is the range of installed capacity of most of the sized hybrid systems studied (26 out of 33 in the table 4.2).

Below is described the most relevant insights from the reviewed articles that are organized according to the total size of the generation technologies or the system as a whole within the following intervals:

- - 1 kW - 10 kW - 30 kW - 1 MW - +1 MW

Relevant insights from HRES research works and study cases sized minor than 1 kW:

- 1 kW Solar Photovoltaic, 1 kW Wind Turbine generator and 1.25 kW fuel cell stack is sized in [21] for a PV/Wind/Fuel cell system configuration for a typical load of 2 kW that could be a telecommunication station or a residential application in isolated islands. The study highlights the contribution of the fuel cell to suppress the fluctuations of the photovoltaic and wind turbine output power and provide a high-quality power to the load.

- 1 kW PV, 1 kW Wind and 1.000 Ah Battery capacity is the experimental set up for hydrogen production powered by a PV/Wind/Battery system in Malaysia analysed by [24]. A model was defined for the system and compared with the in-situ experiment results, thus providing the maturity of electrolyzer technology and the reliability of hybrid systems for those applications.

- For a range of configurations within 850-2.150 W PV, 200-1000 W Wind and 1.5-3 days of Storage, an hybrid PV/Wind/Battery system is sized in [22] under different weather conditions for a remote consumer on the island of Corsica. The remote consumer, with an hourly profile from 3.436 to 4.230 Wh/day depending on the season, can be supplied with the sized hybrid system at a Levelized Cost of Energy (LCE) of 1.29 to 2.12 $/kWh.

- 900 W of a Wind turbine with 320 W or 640 W of PV are analysed in [40] within an off-grid and an off-grid configuration. this work demonstrates that the power mismatch of a smaller sized hybrid PV/Wind (900 W/ 320 W) increases by 28% the daily water pumped while in a bigger sized hybrid system (900 W/ 640 W) it was less than 6% in comparison with the PV or Wind only systems working separately.

- 900 W daily electricity consumption with a PV/Battery system is sized in [9] for a set of houses in southern Algeria and optimized taking into account whether there could be an extra load control or not. For the study case in this work, having a load management strategy contributes to reducing the size of the storage use.

- 148 W photovoltaic panel with a 120 W fuel cell and a 2.54 kWh battery in the optimal size for a 60 W street light in Geneva (Switzerland) described by [52] with a cost of €7.150. It proposes an original time-saving method that comprises two consecutive optimization methods, first genetic algorithms and then simplex ones to obtain the optimal and cheapest size of the stand-alone street lighting system. It shows, as a future development, a software tool with real data (weather conditions, load profiles, etc.).

- 80 W PV/Battery for a street lighting system in islanded or grid-connected mode in China is analysed in [13]. This work states that the cost of Energy in islanded mode is generally 2 to 4 times bigger than for grid-connected systems while it quantifies (in CO2 emissions savings) the environmental benefits for 14 cities in China.

Relevant insights from HRES research works and study cases sized minor than 10 kW:

- 1.7 kW of a passive wind turbine with battery bank in [46] is sized applying a systemic approach with a multi-objective optimization, called IOD method (Integrated Optimal Design). This systemic approach includes the satisfaction of the load power demand and the minimum total cost of ownership (TCO) in the multi-objective optimization. The integrated optimal design was divided into two consecutive optimization processes and the results were analysed in a sensitivity analysis of the PV/Wind system size for the TCO.

- 2,5 kW of a PV/Wind/Hydrogen system for a village in Morocco sized in [20] taking into account different system topologies, components, sizes, life cycle cost analysis and simulations of the load/energy management strategy. This work is part of the HYRESS project: Hybrid Renewable Energy Systems in Rural Settlements of Mediterranean Partner Countries.

- 3 kW Solar/Wind/Diesel isolated system for an island in Greece is sized in [84] implementing the life cycle cost method. The system provides 90 % renewable energy and only 10 % is required from the diesel genset, what is in line with the importance of the local environment's conservation and protection on this island.

- 4 kW Wind/Hydrogen/Battery system is sized in [69] using an optimization strategy considering the hybrid power system as an "energy hub". The resulting system improves by 30% the cost effectiveness in comparison with other layouts.

- 5 kW PV, 2,5 kW Wind and 8x6,04 kWh Battery system is demonstrated in [38] for a household in China. The hybridization of energy sources offers a reduction of the total net present cost (NPC) of 9% in comparison with the PV/Battery option and 11 % less than the Wind/Battery system.

- 6,02 kW PV, 3 kW Electrolyzer, 1,2 kW Fuel cell and 16.49 kWh Battery capacity is the stand-alone system proposed in [32] for a costumer in Spain with a daily load consumption of 200 to almost 700 kW. A model is developed for a PV/Battery/Hydrogen fuel cell and optimized for the size, designs and operation of the system (load power demand, hydrogen energy reserves) while considering techno-economic aspects (commercially available components, cost analysis). Of a total cost of 84.558 $, where the hydrogen system is 56,33 %, it concludes that hydrogen technologies must reduce their cost and increase efficiency to be competitive at a commercial level.

- Also 6,02 kW PV, 3 kW Hydrogen with 10,48 kWh in [31] focus in the technical optimization of the components of the PV/Hydrogen/Battery stand-alone hybrid system using the Simulink Design Optimization (SDO) method of MATLAB and applies it to a case in Spain.

- 9,7 kW PV module (80,4 m^2 installed area) and 2,6 kW heat pump is the optimal system for a typical Danish family house of 2 occupants and 85 m^2 of south facing roof space sized using linear programming in [87] to provide electricity and heat demand with 10 % margin for the capacity size and grid connection. The total cost of this 100 % RES system for a Net Zero Energy Building (NZEB) in Denmark is forecast 75.200 € for 20 years operation, with 53.300 € investment cost, what in total is 180 % more expensive than the conventional configuration of gas boiler and electricity purchase.

- Up to 10 kW of a PV/Wind/Battery is proposed in [59] using a Pareto multi-objective optimization for the sizing and design of the system. It provides the advantage of including conflicting objectives as levelized cost of energy, unmet load, renewable energy wasted and fuel consumption.

- 3,95 m^2 PV and 29,4 m^2 Wind Turbine swept area with a 31,92 kW Battery is the sizing in surface units of an hybrid PV/Wind/Battery system in [23]. The sizing is proposed using a combination of statistical techniques in a methodology called Response surface methodology (RSM). This sizing method is applied for a mobile telecommunication system in Turkey with an hourly average demand of 0,6 to 3,6 kWh, depending on the hour of the day and the season, obtaining as a result this hybrid system for $37.033,9 and an autonomy of 85 to 95 % for the whole year.

Relevant insights from HRES research works and study cases sized minor than 30 kW:

- 9,9 kW PV/ 2,4 kW Wind/ 109 kWh Battery is the most feasible solution of a PV/wind/Battery system in Nice (France), and a 11,7 kW PV only is more feasible for hybrid renewable system in Nicosia (Cyprus) according to [37], while both have quite similar Mediterranean climates. This work points out the high relevance of including climate conditions of the location for the sizing of hybrid renewable systems.

- 15 kW Wind/Diesel/Battery stand-alone hybrid energy system is sized in [49] for a remote community in Greek islands with high wind potential, average above 6.0 m/s. [49] proposes a model and a sensitivity analysis of the optimal configuration of key design parameters as wind potential, capital cost, oil price, battery price and installation costs. The cost effective solution for the Andros island is 0,5 € /kWh for the Wind/Diesel/Battery stand-alone hybrid energy system. A cost-effectivity analysis is key for decision making support since a diesel-only system has cost of 0,61 € /kWh, with a diesel-oil cost of 1,20 to 1,80 € /Kg, while depending on different wind availability of different islands the cost varies from 0,47 € /kWh to almost 0,80 € /kWh.

- 15 kW Wind/Generator and 3 kW PV is the system sized in [105] for the hybridization of a PV/Wind/Generator/Battery system for a residential household and a community desalination system. The hybridization is a more economically feasible sizing than the PV-only or the wind/Generator configurations, independent on the load. The total cost of the hybrid system is less with a reduction of 25% to 32% for a household, while it is 38% to 54% cheaper for the community system.

- 15 kW Wind/Battery stand-alone system optimized in [46] with the objective of minimum total cost of ownership (TCO) what leads to oversize the batteries, thus reducing the depth of discharge by 20% and the number of changes over the lifecycle of the system (20 years).

- 19,8 kWp PV/Battery stand-alone system performance for a remote island in Hong Kong was evaluated in [8]. The article demonstrates how the performance of the operation of the system has to be taken into account in the sizing of the hybrid renewable power system. After a 10-day evaluation of the performance, the over-sizing of the battery bank produces the disconnection of the PV modules and thus the system is not working at its maximum efficiency. It demonstrates clearly the need for a rationales between the sizing of the system and its operation.

- 25 kW of a Hydrogen powered system for a rural health center in India is compared in [103] with grid electricity resulting in a range from 1/2 to 7 times more the cost depending on the input component costs. this work also shares a feasible case study of a dual fuel Diesel/Biomass gasifier pilot power plant of 20 kW powering 85% of the days a non electrified village in India for fourteen years.

- 30 kWp peak power for a PV/Wind/Battery/Fuel cell/Diesel system located in north-western Iran is sized in [41]. It proposes an iterative optimization method where sizing, design and power management strategy (PMS) are taken into account. The analysis of the sizing of the back up system in the operation is very relevant for the sizing and design of the system.

- 30,8 kWp PV and 10 kW Wind is the configuration of a PV/Wind system of 33,6 kW for a desalination unit and potable water production in Tunisia described in [16]. It states also that climatic conditions are key for both the sizing of the hybrid system and the desalination unit.

Relevant insights from HRES research works and study cases sized minor than 1 MW:

- 34,6 kW PV, 30 kW Microturbine and 176 kWh Battery is the hybrid PV/Microturbine/Battery system that [34] compares with the Microturbine or PV only configurations and finds out that the lowest cost of energy is for the Microturbine but very close to the cost of the hybrid configuration. This would mean that any reduction in the price of PV panels or increase in the price of national gas would make the hybrid system more advantageous economically.

- 100 kW PV modules and 9 kW Wind turbine is sized in [96] for a hybrid PV/Wind/Battery system with an optimization method that was developed and applied for a telecommunication relay station looking for the correlation of the cost and the system power reliability under varying weather conditions. For this telecommunication station located in a remote island in China, with a 1.500 W of daily continuous power consumption, the sizing is analysed for different losses of power supply probability (LPSP). For a LPSP of 1% the sized system has a similar cost, around 11.000 US$ for a 2, 3 or 5 days battery configuration.

- 52 kW PV, 300 kW Wind, 163 kW Diesel and 813 units of 2,16 kWh is the hybrid PV/Wind/Diesel/Battery system more suitable than the system with only one energy source for an off-grid application in India studied in [44]. The work proposes an optimum sizing method, called Biogeography Based Optimization (BBO), that, with not much computational simplicity, takes into account in the sizing other complex aspects as the design, control and management optimization.

- 600 kW Wind, 10 kW PV, 608 kW Diesel and 900 Ah Battery system is the hybrid system that [39] applies an adaptative genetic algorithm to match the design optimization from the individual components and applies it at two installations in Taiwan.

- 612 kW Hydro, 110 kW Diesel and 120 Batteries with 60 kW power converters sized in [29] produces 98% of the energy with the microturbine and reduces by 82% the gas emissions versus the system with only Diesel.

- 11.000 kW Diesel and 1.500 kW Wind is the hybrid Diesel/Wind power plant in Japan that [53] integrates the optimization of the operational policy and the sizing of the energy generation components while defining the switching options that bring operational flexibility to the hybrid system.

Relevant insights from HRES research works and study cases sized over 1 MW:

Installed capacity (kW)	- 1kW	- 10kW	- 30 kW	- 1 MW	+ 1 MW
Per generation technology	[21] [24] [22] [40] [52]	[38] [32] [31] [87]	[37] [105]	[34] [96] [44] [39] [29] [53]	[28] [99] [45]
Total system	[9] [13]	[46] [20] [84] [69] [59]	[49] [46] [103]		[81]
Maximum capacity (kWp)			[8] [41] [16]		
Installed surface (m^2)		[23]			
Total 33 articles	7	11	8	3	4

Table 4.2: Sizing of the HRES defined by the installed capacity in kW, kWp or m^2

- 1,9 MW Hydroelectric plant and 9,3 to 28,4 MW PV generation is the hybrid systems analysed in [28] with the objective of increasing the share of renewable and providing an example in Croatia. The security of supply is increased with an upper water reservoir that is able to store a surplus of solar production. The energy produced is more expensive than traditional hydroelectric plants although solar facilities are subsidized. The environmental benefits are evaluated (in savings of CO2 emissions) but they are not monetized.
- 2,5 MW PV, 4,5 MW diesel system and 1 hour storage for a PV/Diesel/Battery system that in [99] is assessed its techno-economic feasibility for a village in Saudi Arabia with 15.943 MWh. This sizing is done using NREL's HOMER software and solar radiation data, and the system provides a 27% PV penetration, 27% of savings in fuel and 24% reductions in carbon emissions.
- 10,5 MW Hydro/Turbine power with upper reservoir and a 30 MW Wind farm is proposed in [45]. The sized wind powered pumped hydro storage system provides an island in Greece, with a electrical demand in 2007 from 40 to more than 60 MW, a combination of renewable energy sources with an acceptable curtailments of 10% of wind energy. The cost of electricity production in Greek islands is around 0,25€ /kWh in 2010.
- 165 MW with a Renewable Energy Supply System (RESS) for the electrical and heating demand in North Aegean (Greece) is more efficient and less costly than a supergrid system, according to [81].

The stages for sizing HRES are listed in [26] as: Pre-feasibility analysis, Unit sizing, Optimization, Modelling and energy flow management. As for modes, it defines that HRES can be sized in stand-alone mode or grid-assisted configuration.

Described below are the key insights from the literature research and study cases around those sizing stages:

- Pre-feasibility analysis:

  [77] is studying the sizing in GW per year scenarios (2010 and 20150) of the technical potential for renewable energy: solar, biomass, wind, and small power, in Pakistan. It is highlighted that the wind based power is being exploited significantly but solar and biomass could help increase the goal of 5% of installed capacity for RES in 2030. [106] focus on PV systems and hybrid configurations and the analysis of optimization techniques. The main output is that meteorological aspects as solar energy, ambient temperature and wind speed have high impact. [26] reviews stand-alone PV solar-wind hybrid energy systems with traditional back-up system as diesel or grid. It states that the unit sizing is based on weather data and maximum capacity while for the modelling design and economic data are tackled in around 90% of the research and very little on control of HRES or utility interactive systems.

- Unit sizing:

  [92] provides a review of methodologies for sizing. It provides an overview of sizing methods, metrics and architectures of hybrid energy systems. According to this review, the sizing methods might be classified as: probabilistic, analytical, iterative or hybrid. As for metrics, referring to the aspects where to focus or the optimization in the design, it describes the followings: Loss of Power Supply Probability (LPSP), Levelized Cost of Energy (LCE), State of Charge of the Battery (SOC,) Level of Autonomy (LA), Expected Energy not Supplied (EENS), Net Present Value (NPV), and Annualized Cost of the System (ACS). Finally, it points out as future trend development of multi-objective sizing methodologies to include the evaluation of different features and the system performance. [12] proposes a tool based in a spreadsheet software that with the solar radiation from NASA SSE data and few more inputs, as load, location, system components and lifetime, provides the size for a PV/Battery system.

- Optimization:

  [41] integrates the power management strategy (PMS) in the sizing of hybrid systems, taking into account that this PMS influences the performance and lifetime of components. The objective of the PMS

optimization and sizing is to minimize the total cost of the system unmet load and fuel emissions. [6] reviews the modelling of photovoltaic systems and hybridized energy with Wind/Battery configuration. It provides a wide overview of the system's key aspects for accurate modelling and highlights relevant findings from past research. Among others, it highlights insights for optimal solar/wind ratio for a minimum investment cost is around 70%, and that batteries contributes to reduce the system frequency fluctuation from solar and wind energy.

- Modelling and energy flow management:

  [19] proposes an optimization- based approach that integrates uncertainty during operation in the design of the hybrid renewable system. This approach enhances a more robust response of the system in the future to potential external or internal variations and identify trade-off between the design and the operations phases. [26]

As for pre and post sizing analysis, both [30] and [10] share cases where the above mentioned stages for sizing are complemented by additional analysis to improve the feasibility of the HRES. [30] analyzes the sizing and design of an hybrid small-scale Hydro/PV/Wind/Bio-diesel generator in comparison with grid extension for a remote village in India. It demonstrates that the combination of technologies improves supply reliability and makes better business case. It also states that while using HOMER well-known software for the sizing of the hybrid system that a pre-analysis, with more detailed evaluation of local demand and type of users, and a post-analysis, with the financing and business model approach, is needed beyond the techno-economic analysis. [10] shares a case study of a PV/Battery system to power a videoconference system in Iraq, identifying the need for those systems by students and University professors to enable access to e-learning.

4.3.5 Technical system design: Operation and Control

The implementation of operation and control strategies with a technical [18] [33] or energy market [107] [8] [60] approach can benefit the global system behaviour and increase the energy efficiency [32] or the energy output up to 10 % [58] as well as benefiting of a reduction of costs or an increase of quality , reliability [39] or robustness [67].

[18] defines power management strategies as a function of the maximum and minimum state of charge (SOC) determining the operation of the electrolyzer and the fuel cell. It defines several modes of operation as for minimum capacity level, fixed or variable power level. The influence of power

management strategies is relevant and it should be considered to forecast the operating and maintenance costs over a period of time.

[33] studies energy management strategies, analyzing a power plan autonomous unit control dealing with the renewable sources, the battery bank, the load demand ad a URFC-FC as back up system. This autonomous unit control is implemented in an experimental set-up at the University in Mexico.

[107] analyzes the implementation of algorithms for Energy Management Systems (EMS) to operate with the minimum Cost of Energy (COE) according to the Load Energy Market (LEM). Demand Response (DR) strategies have been implemented to avoid penalty costs and undelivered power. The effectiveness of the proposed EMS in operation in a LEM is providing about 15% reduction of the COE.

[8] points out the opportunity to train local residents on better utilization of the renewable energy output to avoid situations as when PV array is cut-off because the battery is fully charged, so that demand side management would enable a higher use of available renewable energy.

[60] demonstrates a reduction of 8,5% of the total cost of power generation by using a local energy market (LEM) control algorithm designed to obtain the best purchasing price in a day-ahead market with the maxim utilization of renewable energy sources.

[32] states that implementing control strategies increases by 42% the energy efficiency of the system while maintaining a certain level of back up energy, as in the study in the form of hydrogen energy reserve or SOC of the battery bank. Those control strategies could extent the life time of storage and back up systems and reach a higher energy efficiency, around 67% for the case of study. On the other hand, the study does not consider economic aspects and mentions that hydrogen is not yet competitive.

[58] shares the impact of implementing control strategies regarding power quality, power sources utilization and balancing level, all of this benefiting the energy costs of a micro-grid. A control allowing generation sources to supply the load together in a hybrid solar-fuel cell power plant is proposed reducing the cost by 10%. In addition, a DC micro-grid concept is introduced as a reliable, cost-efficient solution to integrate Distributed Generation (DG) and enabling balancing with consumption.

[39] focus on system reliability and two main indicators, namely loss of load probability (LOLP) and loss of load hour (LOLH). The article shares that a battery with high discharge depth available would make a more efficient use of renewable energy sources and thus reduce installation costs. By considering an adequate capacity of the battery, the life cycle of the storage

system would not imply an increase in maintenance costs in the long run.

[67] studies robust solutions that would be immune against the uncertainty of data on energy loads or data on energy costs. In addition, uncertainty of converter efficiencies more than the nominal schedule can increase the cost from 3,03 % to 11,48 %, that would be the price of robustness, offering a higher protection against worst case scenario of failure.

4.4 Enviromental criteria

The environmental focus so far is present with 3 different approaches: CO2 emissions, tax on carbon emission and Life Cycle Assessment (LCA). Currently in the primary database there a total of 18 publications (7%).

This environmental focus is very little present in the system design research, mainly appointing as information to the CO2 emission of the different configurations. So far, decison-making tools are not translating the environmental benefits into economic value. This is a very high motivation to integrate them among relevant research criteria for more sustainable energy access.

4.5 Objective Function criteria

The Objective Function Criteria (OFC) integrates the relevant criteria of the system design we are considering for optimization in order to serve a defined objective while taking into account the defined constrains. Below it is provided an synthesis of the criteria and how they are considered in several objective functions for the optimal design of off-grid systems introducing renewable energy.

Main two criteria identified for the system optimization are: the minimum Annualized Cost of System (ACS), For system cost, and the required Loss of Power Supply Probability (LPSP), for system power reliability.

[96] objective function integrated both system cost and system power reliability criteria, for an hybrid solar/wind/battery system powering a telecommunication relay station in a remote island of China. The ACS criteria is integrated by the annualized costs of capital, replacement and maintenance. The decision variables for the system optimization are: the number of PV modules, wind turbines and batteries, the PV module slope angle and the wind turbine installation height.

[48] objective function includes both economic and technical performance criteria for a micro Hydro/ Wind system for a case study for a rural com-

munity in India. As for the economic criteria, the minimum Life Cycle Cost is considered, including capital and operational costs. In addition, the technical performance criteria includes both the unit sizing of the system and the system performance operating options for hourly strategy.

[18] just considers as objective function of two technical criteria: Power Management Strategies (PMS) and State of Charge (SOC), for a PV/ Wind hybrid system with Batteries/ Fuel cell/Hydrogen integrated.

[22] proposes a techno-economic optimization for a PV/ Wind system with UPS for several sites on Corsica island. The objective function looks for the appropriate dimensions to provide energy autonomy for a remote typical consumer while having a minimum Levelized Cost of Energy (LCE). The energy autonomy for the consumer is considered via the reliability criteria of Loss of Power Supply Probability (LPSP). For the LCE criteria, it is considered as the ratio of the total annualized cost and the annual electricity delivered. For the studied system, the LCE obtained between a range of 1.29 and 3.93 USD/kWh for the different sites and several optimal configurations identified.

[41] defines the optimization of the Power Management System (PMS) of an hybrid energy system, including different renewable and non-renewable generators and storage technologies, as a mixed-integer non-linear multi-objective problem. The objective function cover economic, technical, quality of supply and environmental criteria. It proposes a case study in Iran for a PV/ Wind/ Diesel/ Hydrogen/ Battery system. The different criteria considered are: for economic, the minimization of the overall cost of the system discounted of the year of installation (so called Net Present cost, NCP), for technical and quality of supply, the Loss of Load probability (LPSP) equivalent of the total unmet energy, and for environmental, the minimization fuel emissions by diesel generators for the lifespan of the system.

[68] proposes the optimization of the energy mix to supply electrical and thermal energy for multiple consumers at the lowest price paid by consumers. The consumers are 60 houses in a tourist resort in Timisoara (Romania), powered by wind, biogas, fuel cell, PV panel hybrid system or grid connected. For this, different scenarios of hybdrid systems have been analyzed obtaining a range of price paid from consumers from 0,40 USD/kWh, for a grid connected PV panels and methane gas boiler, to 0.14 USD/kWh, for a wind farm and gas methane boiler, taking into account 0,20 USD/kWh is the energy price to be bough/sold via the grid connection.

[108] provides an extensive review of evaluation criteria for the design of hybrid energy systems, including technological (6), economic (7), socio-political (2) and environmental factors (2). This review also includes a sum-

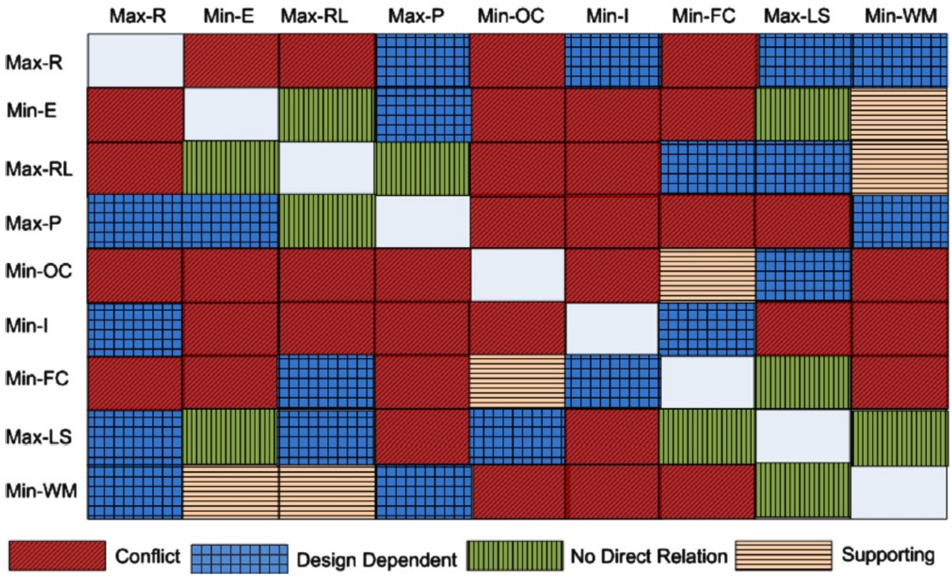


Figure 4.3: Relation between conflicting objectives. Max-R: maximize revenue, Min-E: minimize emissions, Max-RL: maximize reliability, Max-P:maximize production, Min-OC: minimize operating cost, Min-I:minimize investment,Min-FC: minimize fuel cost, Max-LS: maximize lifespan, Min-WM: minimize waste.)

mary of commercially available tools (6) for the sizing of system components, sizing methodologies (6) and control and energy management strategies (4).

[109] review identifies conflicting objectives, beyond the minimization of costs, for the optimization of renewable energy systems. Most of the objectives identified, 6 out of 8, are conflicting with the minimization of cost.

Those objectives identified as conflicting with economic criteria, identified by [109] as shown in 4.3 are: maximization of renewable, minimization of emissions, maximization of reliability, maximization of production, minimization of investment, and minimization of waste. The only supporting objective with the minimization of cost is the minimization of fuel cost, while the maximization of lifespan is design dependent. [109] also identifies an increasing research activity in the area of optimization methods for renewable energy sources, while spotting non-linear optimization methods as the most popular so far.

There are several design and modelling open source tools beyond HOMER:

- Open Energy Platform part of the project open-eGo of the German

Government [110], has available a database including grid, demand, environmental, emission, and other different datasets.

- energyRT [111] is an energy systems modelling R-toolbox to develop Reference Energy Systems (RES) models, including a typical linear, cost minimizing model, that can be solved by GAMS.
- REEEM project Energy System Modelling Project [112], gain a clear comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a low-carbon energy society.
- Holistic Urban Energy Simulation (HUES) Platform [113], optimal design and operation of distributed renewable multi-energy system at the level of buildings and districts.
- Load ProGen software [114] for daily load profiles estimates for rural consumers [91].

4.6 Guidelines for a more sustainable off-grid system design

Main considerations and guidelines for a more sustainable off-grid system design:

1.- Use COE enabling comparison for different size systems, applications and countries as in figures 4.2 and 4.1. In addition, the COE enables the comparison with existing energy technology generations and systems:

- Solar cost of PV technology, minor than 0,20 USD/kWh [99], while PV reached grid parity in 2013 [115].
- Diesel only systems [56], with costs higher than 1 €/kWh.
- Diesel fuel price, mentioned in chapter 1.
- Grid availability, including the concept of radio for break-even distance.
- Grid price, different per countries.

2.- Focus on main cost drivers of the system components,as they are estimated to be the investment costs and the batteries such as detailed below:

- 70% to 80% are investment costs [105] [38].

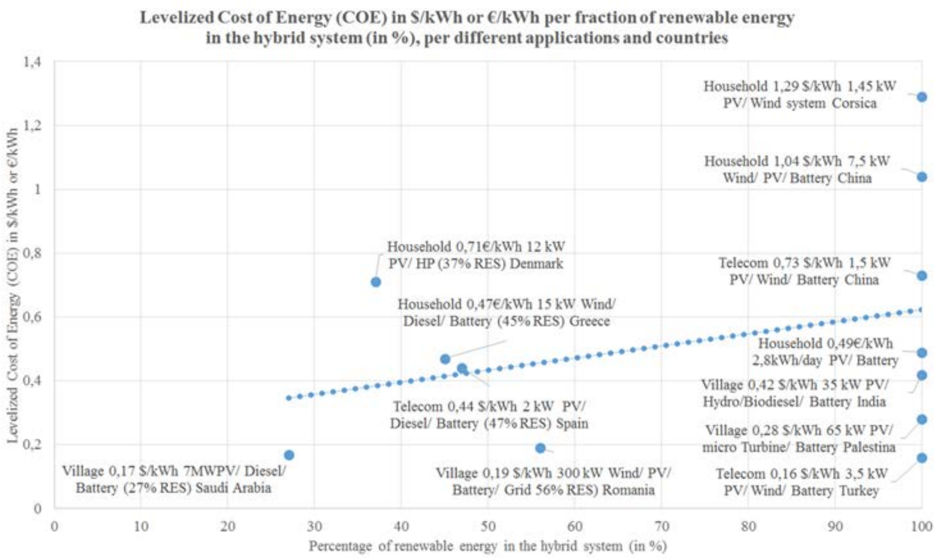


Figure 4.4: Levelized Cost of Energy (COE) in USD/kWh or €/kWh per fraction of renewable energy in the hybrid system (in %), per different applications and countries)

- 15% to 35% are batteries costs [105].
- 1% to 5% are operation and maintenance costs [23] [87].
- around 1% of costs are dedicated to electrical converters [52].

The investment costs are the highest % of the total energy cost, around 75% of the total. After this, batteries are the second most relevant cost driver with around 25%. This link to the relevance of the financial part, analyzed regarding the integrated value chain proposed in chapter 5. This also links to the relevance of including reliability criteria to the economic analysis and the study of back-up systems, as introduced in this section.

3.- Translate the environmental benefits [101] [99] to economic values, looking for a higher presence of renewable energy as in figure 4.4.

The importance of considering other criteria besides the cost is more and more important with all the change drivers highlighted in this work. In the analyzed case study in chapter 2, an increase of only 1% in the optimum cost the system almost double the fraction of renewable resources up to 47% (figure 4.5).

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%

Figure 4.5: Key criteria per scenarios and % of variation from the optimum cost (Scenario A) in case study 2)

4.7 Conclusions regarding design criteria for HRES

The analysis of innovations regarding the system design for Hybrid Renewable Energy Systems (HRES) have identified untapped potential for the research community. Currently system design is mainly technically driven with some economic analysis regarding return on investment.

The need for affordable tools for decision-making integrating technical, economic and environmental aspects would ease the roll-out of HRES. Those identified opportunity areas for future innovations would have many benefits as: multi-disciplinary approach to develop innovative business models and other enabling areas, more integration of real-life cases in research works, and introducing the environmental benefits in decision making to encourage more investments.

Easy to use open decision-making tools integrating multi-stakeholders relevant aspects would have future opportunities. Regarding decision-making tools, the most currently used optimization algorithms and software tools for the design of HRES have been included. Following this analysis, an easy to use guideline for a more energy sustainable system design is proposed introducing the most relevant criteria. The validation of the optimization algorithm is proposed and compared with a published study case using HOMER, the most well known design tool for HRES. This guideline offers the possibility to implement an easy to use decision-making tool for the early stages of the system design.

Chapter 5

More integrated approach beyond system design and economic criteria

Following the lessons learned in chapter 3 regarding the increasing need and trend of more research in HRES beyond the system design focusing on the technical arena, and the guidelines proposed in chapter 4 to include decision scenarios beyond the most common economic criteria, the need for a more integrated approach in the study and development of HRES is increasing.

In order to tackle this growing need for a more integrated approach beyond system design and economic criteria, an integrated value chain for HRES is proposed. Firstly, an overview of multi-disciplinary aspects beyond technical, economic and environmental criteria is provided. Secondly, an integrated value chain for HRES is proposed.

Beyond a more integrated approach, this research suggests the need for more collaboration within the research community, companies and stakeholders in multi-disciplinary innovations. For this purpose, the website ElectrifyMe www.eletrifyme.org has been created, sharing the findings of this PhD work and fostering future research collaborations for more HRES and more sustainable energy for all.

5.1 Value chain for more integration of renewables off-grid after optimal system design

Following the conclusions in chapter 3 and chapter 4, and following the need for a more integrated approach in the study and development of HRES I propose an integrated global Value Chain for those systems defined below.

Beyond the system design focusing on the technical arena, [116] proposes a supply chain for an energy Kiosk as Community Charging Station (CCS) pointing out 4 key success criteria: commercial viability, positive community impacts, dissemination of improved lighting, and provision of credits.

Beyond the most common economic criteria, [95] defines a conceptual framework of key sustainability criteria along the value chain from studying pico-PV for electric light systems. The value chain stages proposed includes: product design, product supply, retail and end-use. Main aspects of this sustainability criteria are: easy and safe operation of the system, a system for product return is established, retailers understanding the target market, and end-user being aware of the products existence and benefits.

Taking into account the broader scope of value creation for HRES, an overview of multi-disciplinary aspects such as financing, business models, energy markets, technology development for system integration, policy, regulation, knowledge management and transfer, and valorization is provided in the following section.

After this overview of multi-disciplinary aspects beyond system design creating value for HRES, an integrated value chain for HRES is proposed defining primary thematic areas, mainly regarding technical and economic design studied in chapter 4, and secondary thematic areas being introduced in this chapter.

5.1.1 Financing, business models and energy markets

Key enabling areas for closing the gap of innovation in HRES systems towards the market are financing and business models [117]. The massive deployment of renewable energy in off-grid systems requires appropriate and sustainable financing schemes and business models. In order to develop them multi-disciplinary research is needed using tools, models, methodologies, stakeholders involvement and support mechanisms, just to mention a few:

- Implementation of strategic and financial tools (SWOT analysis, case studies, feasibility evaluations, etc.). [11] carried out an evaluation of the feasibility study of a smart street light system with integrated solar panels and free maintenance batteries. This evaluation included the development of a case study in a remote village that provided the cost savings per year of the new system over the conventional one.

- Development of models (energy models, value chain, supply chain, etc.). [82] developed interactive energy models and implemented in a SWOT analysis to promote the integration of renewable energy sources for more competitive and sustainable islands. [95] analysis key criteria for successful sustainable development of pico-PV technology projects. The results of the key factors of the value chain are also interesting for HRES projects since they focus in the supply chain part: understanding the target market and the maintenance or product return availability.

- Design of methodologies (strategic analysis integrating the end users and the community, assessment of the current and future potential of renewable energy technologies, etc.). [85] develops a strategic analysis methodology that integrates the community/end user perspective: from the range of energy demand levels to their values, ideas and expectations. This approach was used in a case study of an isolated Pacific Island. This methodology contributes to closing the gap of traditional techno-economic analysis towards a broader concept of feasibility and sustainability that includes social, economic, policy and environmental context.

- Integration of stakeholders (industry and scientific community) for real-life testing of technology transfer potential of research and innovations towards market for more innovative business models. At [118] the German Renewable Energy Research Association (FVEE) and its member institutes together with industrial companies develop technical solutions, test systems and components, and run trials in realistic conditions. Integrating industry in the scientific community work and having more research and innovation within industry is beneficial for market development of HRES and the implementation of innovative feasible business models.

- Availability of efficient and sustainable financing support mechanisms. [119] proposes a Feed-in-Tariff scheme that awards the kWh produced by renewable energies for a limited period of time. This would support the investment donations for off-grid systems towards long-term sustainability of energy development projects. This proposal has been evaluated for isolated regions in Ecuador for the integration of photovoltaic systems in comparison with stand-alone diesel ones. Feed-in-Tariff is one financial support mechanism to be further studied and accordingly integrated in policy and regulatory framework discussions.

Financing and business models still have minor interest for the research community. It is clear in light of the current challenge of the opportunity for multi-disciplinary research to develop innovative business models.

5.1.2 Technology development for system integration

Within technology development we find many research for single and separated technologies of renewable energy sources present in HRES systems but not for the system integration perspective. System integration is a key enabling area for future research focus as it is described for all energy technologies in the new SET-Plan Integrated Roadmap of the European Commission [120].

5.1.3 Policy and regulatory framework

Policy and regulatory framework is one of the most efficient and powerful tools on the hands of local and national governments to enable an accessible and sustainable energy future for their societies.

- Policy makers and regulators are key for Energy Policy activities, among others: energy planning [121][77][122], energy market regulation [123], renewable energy support [76] and awareness [73], financing schemes for clean technology or the reforms of the electric power sector [124]. Any of these policy and regulatory activities can have a strong impact in the adoption of renewable energy sources and HRES and some more detailed examples are referred to below.

  Regarding energy planning, [121] [77] analyses the potential of power generation via current and future renewable energy technologies in Pakistan. The study includes the geographical, technical and economic potential. Other authors mentioned in this work also consider other potential types as practical, realisable and market. Those potential studies are very valuable when developing national energy policy towards energy sustainability. In [122] the wind energy potential in Ethiopia is reviewed and linked with the installed electric power capacities and the current energy policy of the country. The study revealed the renewable energy potential for wind, geothermal, and hydropower. The latest already well-known because Ethiopia relies on hydroelectric plants for the most of their energy production. The wind energy potential has been translated via the country energy policy, so called five year Growth and Transformation Plan (GTP), into eight wind farms and some hydropower plants.

  In the framework of energy market regulation, [123] studies the options to meet the increase of energy demand in Africa with substantial renewable energy sources. The total system cost within a continental trade scenario is 21% less than the national business as usual current situation. The development of regulatory framework and policy at transnational level can benefit the economies of scale in continental transmission grid expansion and therefore contribute to a more renewable and sustainable energy future. Within renewable energy support, [76] analyses the ongoing low-carbon city development in eight cities in China. Preliminary results about the integration of renewable energy and energy saving technologies, with national and local support policies, mainly for solar PV and heat pump systems are promising for reducing electricity demand and related carbon emissions. Awareness also plays a relevant role, as highlighted in [73] regarding the need for raising awareness and investment in renewable energy technologies, in particular for biomass energy in development countries. It recommends specifically to sub-Sahara African countries to fast track the development of renewable energy policies according to local realities and being aware of the global current paradigm.

The reforms of the electric power sector in developing countries can be an opportunity for renewable energy depending on the chosen policy and legal framework established by the country and local government. In the case of Argentina studied in [124], the wind energy potential was inefficiently promoted by the legal authorities at the time of the electric power sector reform. It has been a later joint venture of companies who are leading its development and building up wind farms regardless the initial lack of national support.

- Policy and decision making actors need support of reliable data [125] and advice, whether it comes from international institutions or provided via indicators or indexes that enable to evaluate their progress towards energy sustainability. On top of this robust information need for decision making, the integration of stakeholders [82] and the involvement of local and private communities [126] are paramount for the follow-up of progress.

  Existing indicators monitor among other energy access, as in [125] where in particular it is analysed the access to modern energy in Ghana. The policy and regulatory framework recommendations after this study are related to enhance positive progress and alleviate the supply constraints by means of: establishing a power trading company, new business models like SME-based mini-grids and off-grids and rethinking subsidies, among others.

[82] shares best practices about the integration of stakeholders via a workshop with a competitive game based in an energy model. The energy model and tools were developed in the framework of the "cradle to cradle" project for islands. It proved that those tools contributes to the collective social learning process for more renewable and sustainable energy model in some islands.

Similarly [126] emphasizes the need for global policies in countries with low access to electricity, especially in Sub-Sahara Africa. In order to achieve an energy sustainable development, policy should take into account renewable energy nd reduce the emissions from fossil fuels. It is a must for government, local and private communities to work together for rural electrification successful projects that would deliver also job creation and have a direct benefit for the local people.

- As indicators and progress monitoring tools there are several measuring aspects as access to energy and energy development [80], energy sustainability or knowledge based economies [88].
- International institutions as the World Bank [127], the UNESCO Chair for Sustainable Development [80] or the World Energy Future council [65] or other bodies with global scope as the International Institute for Sustainable Development [128], just to mention some, provide advice and tools to support policy makers.

5.1.4 Knowledge management, education and training

Global challenges require global solutions and knowledge based sectors, as it is the renewable energy technologies sector, it is key a sufficient knowledge management and stakeholders cooperation to achieve a massive and sustainable development. In [70] an extensive review of scientific production of renewable energies, from 1979 to 2009, highlights the degree of relationship between this research and the location of the energy resources studied. It is observed that a small group of countries concentrate most of the scientific production but they are not necessarily those with the greatest availability of this resource. In [71] the knowledge management mapping and gap analysis in renewable energy shows a week current situation. It highlights that so far it is limited to information sharing and awareness raising, followed by policy assistance and technology transfer. Multiple opportunities for joint research activities, standardization, certification, close implementation, coordination and evaluation, among others, remain under developed. Knowledge management and exchange of researchers and professionals is very important to close the current gap and facilitate the introduction of renewable energy in off-grid systems.

Whether the scientific production is not necessarily conducted in the regions where the innovations could be implemented or whether the knowledge management is still restricted to information sharing and awareness raising, the potential for high added value actions on this regard is untapped. Similar situation of under development for education and professional training for HRES. Those could benefit and share synergies with knowledge management networks and initiatives.

5.2 Proposal for a more integrated Value Chain for HRES

The integrated Value Chain for HRES proposed is defining the creation of value with the different activities for all involved stakeholders. Inspired in the Porter's Value Chain concept [129] [130] and the definition of a Supply Chain for Renewable Energy [131], this integrated Value Chain for HRES is proposed below 5.1.

Porter [129] developed the concept of Value Chain as the chain of activities creating and adding value, so called value flow, for all stakeholders involved. Following this, Porter also defined a broader concept of value including economic, social and environmental values [130] where primary activities are facilitated by support activities, and those second run in parallel with primary activities. In [131] the Renewable Energy Supply chain is defined and studied. The study provides recommendations to stakeholders for the initiation and overcoming of barriers for the development of renewable energy use. However, any other research has been spotted working in the value or supply chain in the use of renewable energy. The current review provides an overview of what activities are most covered by scientific community nowadays.

The proposed integrated Value Chain for HRES takes into account the different stakeholders and how their primary and support activities are creating and adding value for them and for the costumers or end users, in a broad sense of market, society and environment welfare. Primary activities are also referred as sectorial areas and support activities as enabling areas. As described in figure 5.1, the primary activities and sectorial areas of the global Value Chain are in vertical while the secondary activities and enabling areas are below in the horizontal axis running in parallel.

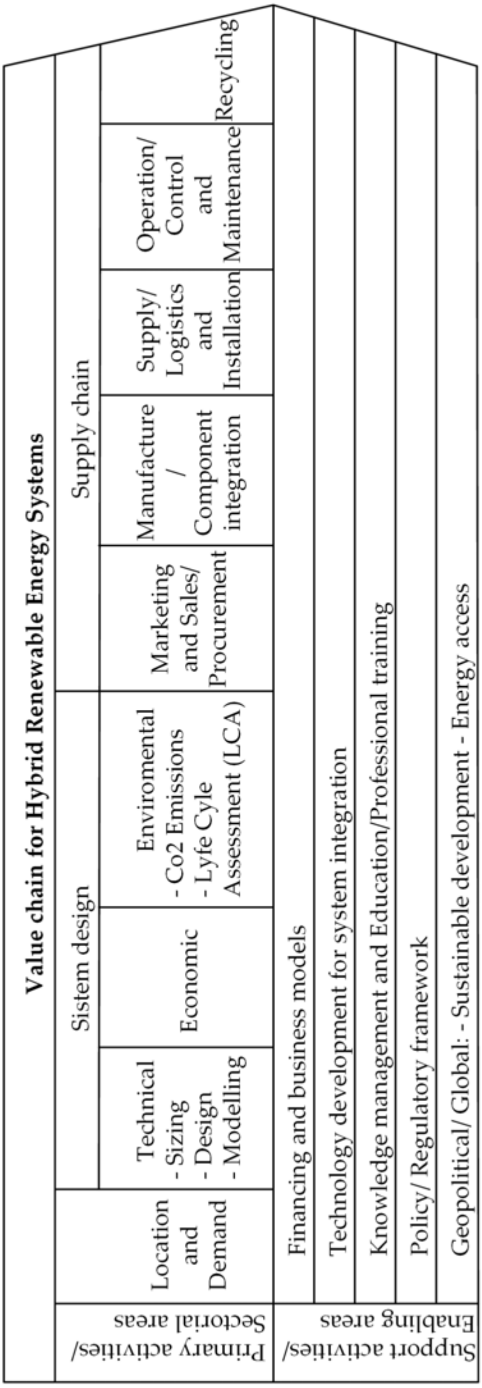


Figure 5.1: Integrated Value Chain for Hybrid Renewable Energy Systems (HRES) proposed.

Location	Technical			Economic	Environment	Operation
	Sizing	Design	Modelling			
3	52	20	25	37	10	25
[14] [15] and as review: [101]	[96] [22] [21][99] [23] [52] [19][45] [49] [134] [24] [32] [87] [84] [69] [20] [8] [59] [37] [41] [38] [16] [105] [30] [34] [81] [103] [40] [44] [53] [136] [39] [14] [15] [13] [28] [9] [46] [29] [10] [12] [31] [57] [47] [42] [35] and as articles: [26] [26] [6] [92] [106] and [77]	[22] [21] [99] [52] [20] [37] [38] [103] [40] [44] [15] [13] [28] [10] [47] [64] [11] [68] [58] and as review: [72]	[96] [52] [19] [87] [84] [20] [41] [53] [39] [28] [10] [31] [47] [42] [68] [58] [104] [67] [50] [132] [33] [17] [18] [48] and [97]	[96] [7] [60] [23] [52] [19] [49] [32] [87] [84] [69] [41] [132] [25] [11] [30] [34] [103] [53] [39] [13] [9] [46] [10] [48] [47] [97] [42] [12] [58] [44] [105] [35] and as review: [6] [101] [92] and [77]	[132] [39] [13] [57] [47] [97] [52] [135] and as review: [26] and [101]	[96] [60] [107] [19] [32] [133] [67] [8] [50] [41] [43] [132] [25] [33] [44] [39] [18] [58] [9] [64] [31] and as review: [26] [6][61] and [66]

Table 5.1: Scientific research in Primary activities and Sectorial areas of HRES, period 2005-2015

5.2.1 Primary activities and sectorial areas

In primary activities of the HRES global Value Chain there is significant research related to the System design, mainly devoted to the technical and economic areas. See in table 5.1 the number of publications for several of these primary activities.

Sectorial areas and primary activities (in vertical) are:

- Location and Demand
- System design (Technical (Sizing, Design, Modelling); Economic; and Environmental(CO2 Emissions, Life Cycle Assessement (LCA))
- Supply chain (Marketing and Sales/Procurement; Manufacture/component integration; Supply/Logistics and Installation; Operation/Control and Maintenance; and Recycling) ...

See in table 5.1 the number of publications for several of these system design activities.

5.2.2 Support activities and enabling areas

As support activities, see table 5.2, the most popular enabling areas found for scientific production are in order of relevance those related to: Sustain-

Financing/ Business model	Knowledge management/ Education	Policy/ Regulatory framework	Sustainable development	Energy access
6	2	15	20	12
[95] [82] [11] [85] [119] [118]	[71] [70]	[123] [76] [121] [80] [73] [125] [126] [71] [88] [122] [82] [65] [128] [127] [124]	[74] [95] [123] [104] [76] [137] [73] [7] [52] [72] [140] [88] [122] [82] [79] [14] [13] [85] [128] [48]	[54] [51] [55] [125] [75] [126] [138] [139] [141] [118] [10] [36]

Table 5.2: Scientific research in Support activities and Enabling areas of the HRES Value Chain, period 2005-2015

able Development, Policy/Regulatory framework and Energy Access.

Enabling areas and support activities (in horizontal)are:

- Financing and business models
- Technology development for system integration
- Knowledge management and Education/Professional training
- Policy/Regulatory framework
- Geopolitical/Global (Sustainable Development, Energy Access) ...

5.3 Proposal for more collaboration in multi-disciplinary research

The challenge for research community The role of research community to transfer state-of-the-art technology and innovative business models to contribute to achieve universal energy access in 2030 according to the Sustainable Energy for All (SE4ALL) scenario.

In order to identify what opportunities can be identified after the contributions from recent years research, a methodology has been built and applied during the duration of this PhD work. Most relevant innovations identified for the purpose of this research have been detailed in previous sections and chapters. In addition, there is a significant untapped research potential in using the primary database for other research questions and multi-disciplinary research collaborations.

Knowledge transfer and research valorization In order to facilitate the transfer of the knowledge developed during this PhD work and to foster future research in multi-disciplinary perspectives of HRES, the website ElectrifyMe www.eletrifyme.org has been designed and developed as detailed in the next section.

5.4 ElectrifyMe www.electrifyme.org

The main objective of the ElectrifyMe website initiative via www.electrifyme.org is to foster future multi-disciplinary research in stand-alone HRES while sharing the developments and findings during this PhD work.

The main target audience for this website initiative are researchers and professors who are looking for identifying research opportunities to integrate renewable energy systems off-grid. This would be also open for companies, public bodies and other stakeholders interested in HRES.

In order to offer this two value propositions, as sharing raw information and valuable insights, to the research two main sections accessible via a simple main landing page are provided:

- Main page guiding to "Discover" and "Dynamic Charts".
- "Discover" page sharing the detailed list of innovations.
- "Dynamic charts" page visualizing main selection criteria: publishing country, thematic focus and year.

5.4.1 Main page to access "Discover" & "Dynamic Charts"

The main page of ElectrifyMe, displayed in figure 5.2, is guiding to "Discover" and "Dynamic Charts".

5.4.2 Discovering and diving into the list of innovations

The "Discover" page of ElectrifyMe, displayed in figure 5.3, is sharing the detailed list of innovations availables in the primary database, mainly in the form of research publications.

Each of the innovations included in the list has the following information in the description: Country, Year, Thematic Focus, Energy sources, Title, and URL.

The "Discover" page has the capability to search the publications by any of those four criteria. This page also has enabled an open search field for

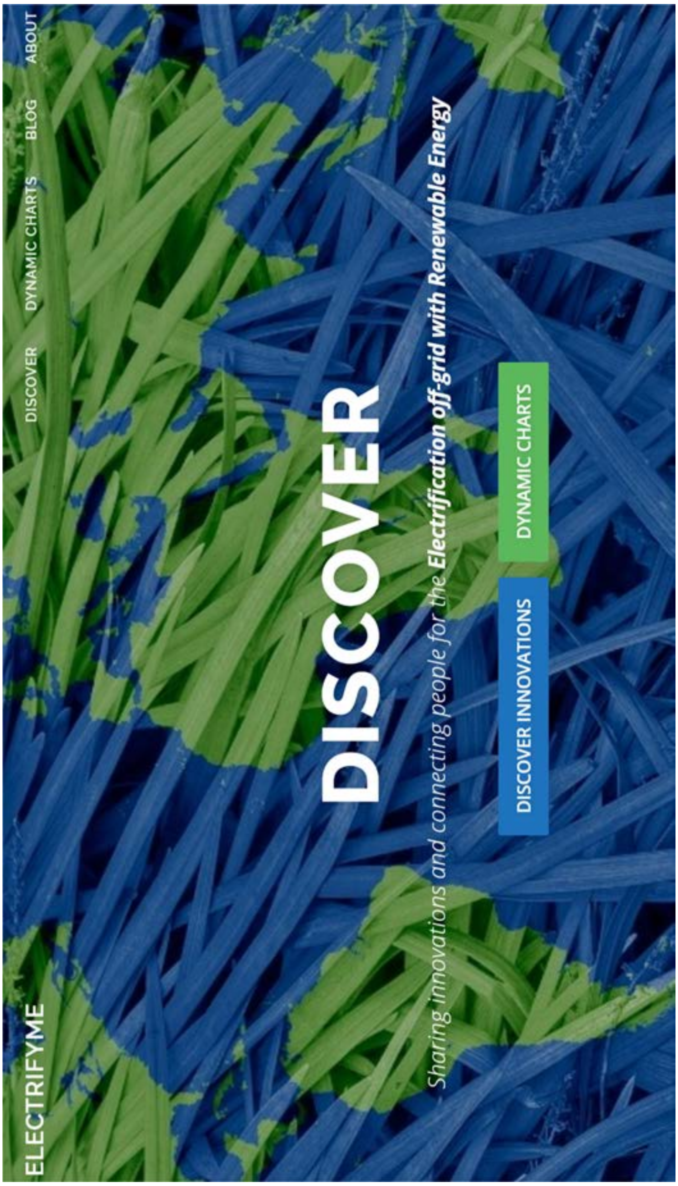


Figure 5.2: Main page of ElectrifyMe www.electrifyme.org guiding to "Discover" and "Dynamic Charts".

Figure 5.3: "Discover" page of ElectrifyMe www.electrifyme.org sharing the detailed list of innovations.

introducing free text and scanning the full list of innovations for a more tailored search.

The description of the categories in "Thematic Focus" and "Energy sources" are resulting from the insights from chapter 3. The lists of values available for each of those two categories are detailed below.

Category "Thematic Focus":

- Tech- Location and Demand
- Tech- Design
- Tech- Modelling
- Tech- Sizing
- Tech- Operation and Control
- EcFin- Economic/ Costs
- EcFin- Financing, business models and energy markets
- Env- Environmental
- Others- Knowledge management, Education and Professional training
- Others- Policy and Regulatory framework
- Others- Sustainable Development
- Others- Energy Access

Category "Energy sources":

- PV
- Wind
- Hydro
- Diesel Generator
- Fuel cell
- Biomass
- Biogas

- CHP
- Grid
- Gas
- PV/ Wind
- PV/ Grid
- PV/ Hydro
- PV/ Wind/ Hydro
- PV/ Wind/ Grid
- PV/ Diesel
- PV/ Wind/ Diesel
- PV/ Wind/ Hydro/ Diesel
- PV/ Hydrogen
- PV/ Fuel cell
- PV/ Wind/ Fuel cell
- PV/ Wind/ Hydrogen
- PV/ Wind/ Diesel/ Fuel cell
- PV/ Hydro/ Biodiesel
- PV/ Wind/ Diesel/ Grid
- Wind/ Hydro
- Wind/ Diesel
- Wind/ Hydro/ Diesel
- Wind/ Grid
- Wind/ Gas/ hydro
- Biomass/ Fuel cell

5.4.3 Dynamic visual overview per four selection criteria

"Dynamic charts" page is visualizing main selection criteria: publishing country, thematic focus and year.

Each of the "Dynamic charts" pages has enabled selecting different analysis perspectives as: Country, Year, Thematic Focus, or Energy sources. The "Discover" page has also the capability to search the publications by several of those four criteria.

Dynamic charts per publishing country

The "Dynamic charts" page is visualizing publishing countries, as displayed in figure 5.4.

Dynamic charts per thematic focus

The "Dynamic charts" page is visualizing the thematic focus of innovations, as displayed in figure 5.5.

Dynamic charts per yearly trend

The "Dynamic charts" page is visualizing the year of publication of innovations, as displayed in figure 5.6.

5.5 Conclusions for a more integrated approach

After an analysis of those many different focus that goes from technical and economic, to environmental, regulatory or political aspects an integrated value chain for HRES systems has been proposed.

Sharing those findings and nurturing the primary database with new entries would enable sharing trends on renewable energy in off-grid power system as well as identifying untapped research opportunities and future potential innovations to enhance the roll-out of renewables in stand-alone systems. Knowledge transfer and research valorization is having an impact in real-life installation in different countries. This can be replicated in other countries and research communities.

Valuable networking contacts among researchers would enable many untapped research opportunities. The role of research community to transfer state-of-the-art technology and innovative business models will be essential to achieve the SE4ALL goals by 2030. After sharing innovations and providing tools, facilitating networking among researchers is proven to be a

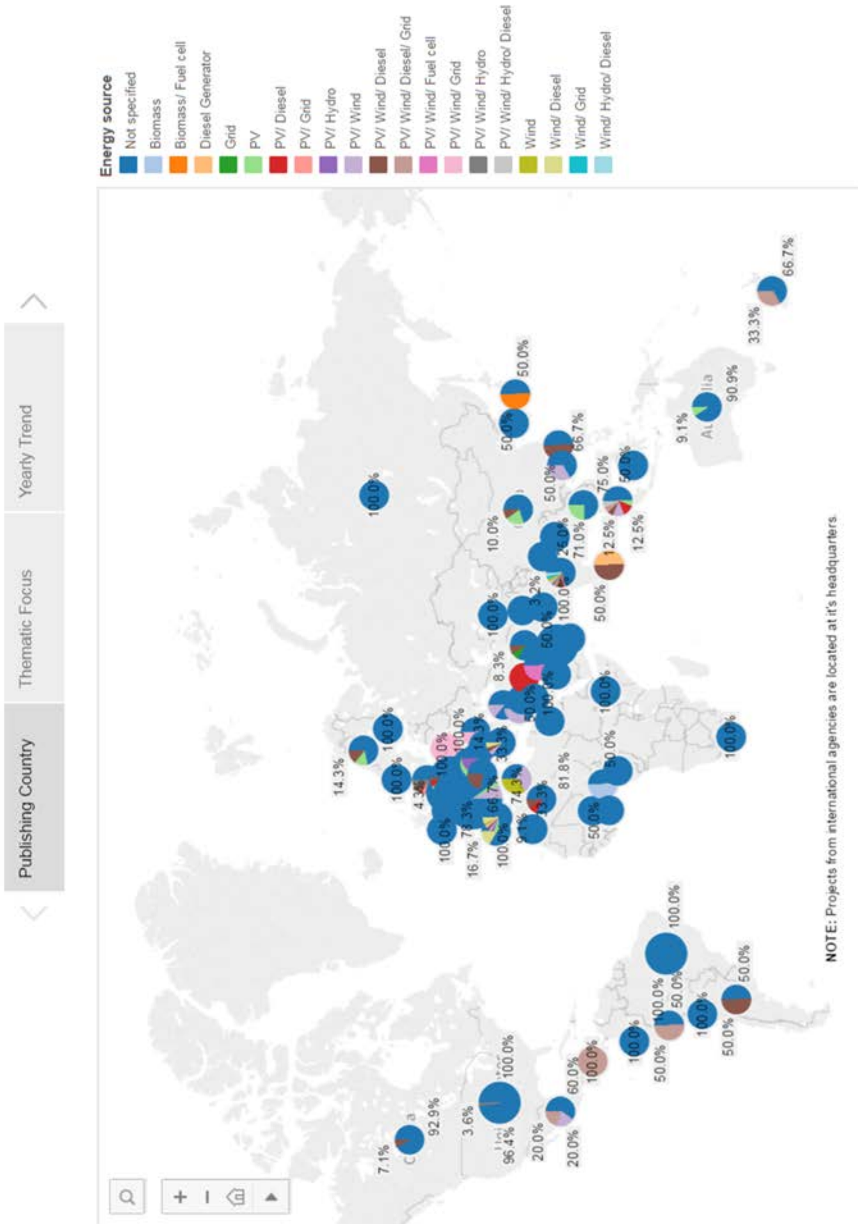


Figure 5.4: "Discover" page of ElectrifyMe www.electrifyme.org sharing an overview of publishing countries.

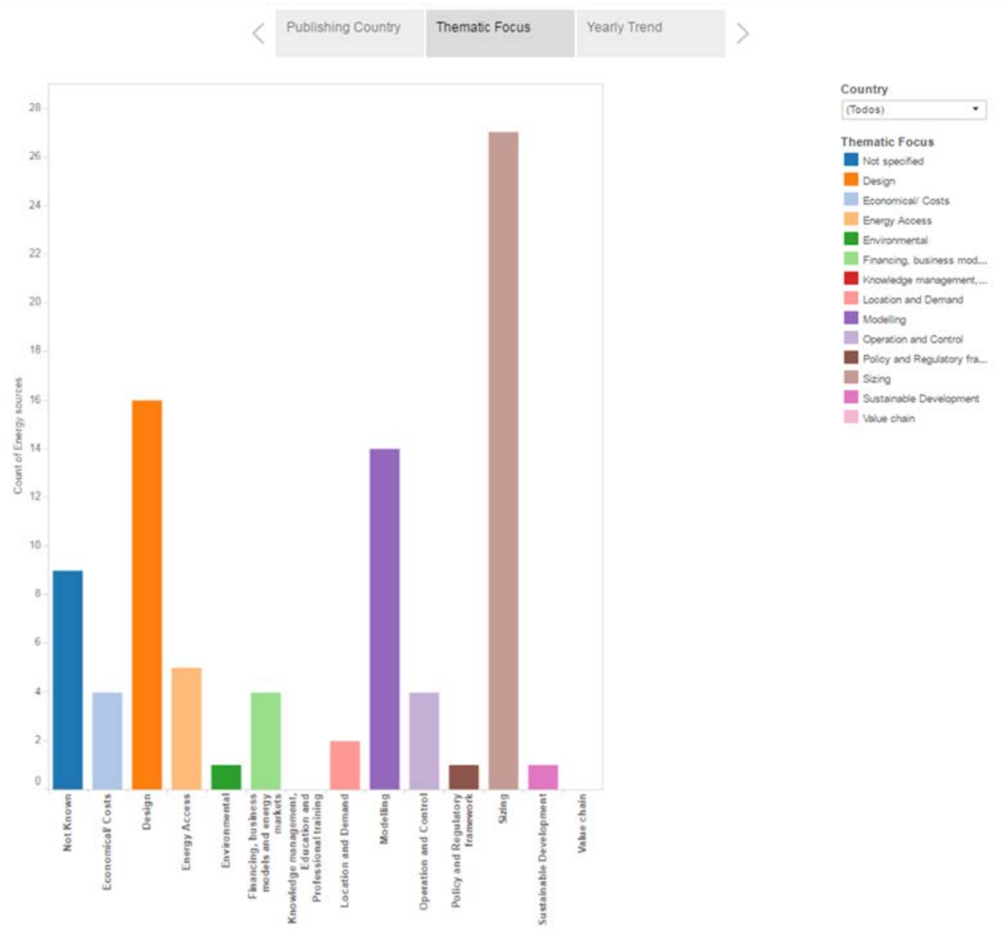


Figure 5.5: "Discover" page of ElectrifyMe www.electrifyme.org sharing an overview of the thematic focus of innovations.

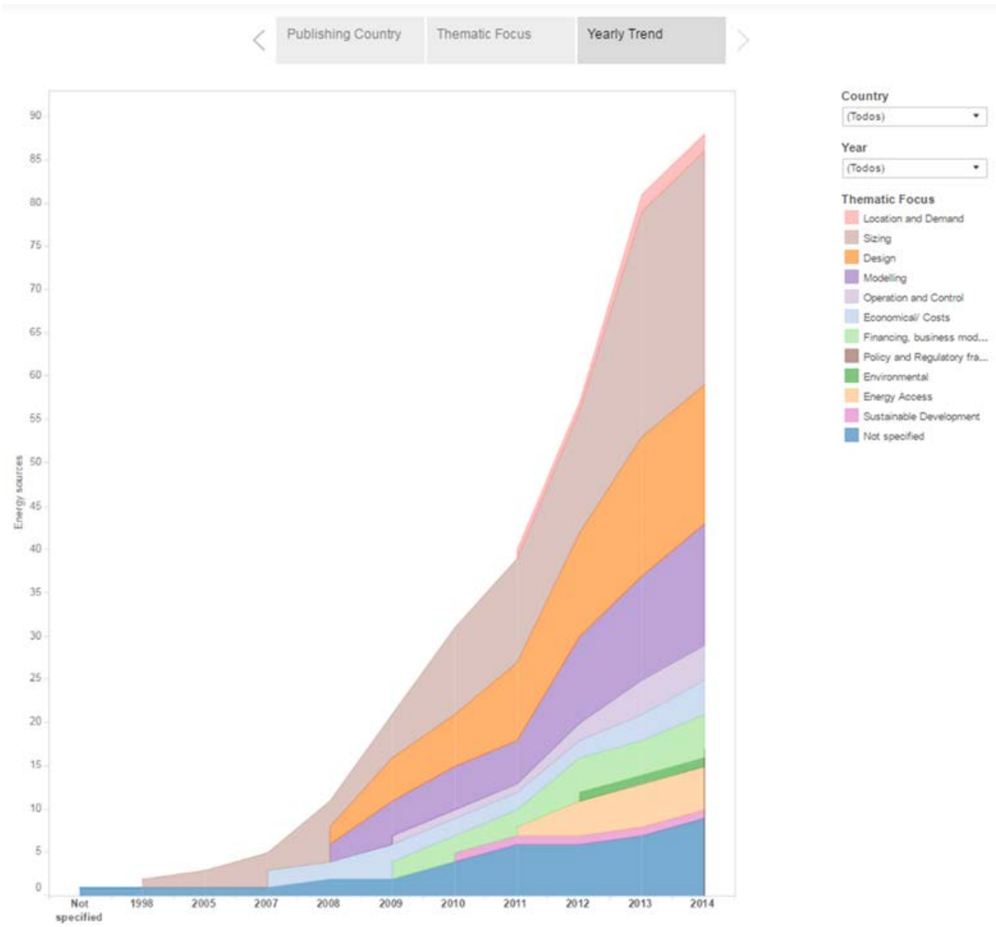


Figure 5.6: "Discover" page of ElectrifyMe www.electrifyme.org sharing an overview of the year of publication of innovations.

powerful action to tackle untapped research potential with multidisciplinary and international teams. The website ElectrifyMe www.electrifyme.org has been created in order to facilitate research community to discover innovations and share projects. This initiative aims the research community to benefit the future massive roll-out of HRES by: sharing innovations, encouraging knowledge transfer and facilitating networking.

Chapter 6

Conclusions

Knowledge, methodologies & tools are provided in this PhD work for more stand-alone hybrid systems creating value for more of the stakeholders involved.

After reviewing the latest innovations in HRES per thematic focus an integrated value chain for those systems has been proposed and multidisciplinary research opportunities have been identified.

Identifying the need to include the environmental aspects in early stages of the decision-making has lead to propose an easy to use guideline integrating most relevant criteria for the design of stand-alone renewable power systems.

Finally, the research opportunities identified and the untapped potential of transferring latest innovations have result in the creation of the website ElectrifyMe (www.electrifyme.org) to enable valuable international networking contacts among researchers and encouraging multi-disciplinary research.

"Knowledge, methodologies & tools" are powerful contributions by research community and innovators to foster more sustainable energy for all.

6.1 Originality of the research contributions

The originality of the work strives on identifying the contributions by research community to a world challenge as it is sustainable energy access. This universal challenge is mainly driven by public international bodies and Non-Governmental-Organizations (NGOs) while the impact by research community contributions remain less known and recognized.

Its originality also is explained by a broad and holistic approach integrating in the research different perspectives as social, economic, technical and energy source environmental. Another particularity of this research is that it has a 10 year long period scope, from 2005 to 2015, enabling world wide trends identification in the introduction of renewable in stand-alone power systems.

Due the globalization and dynamism of energy scenarios, a web site has been developed which allows open-access appraisal mechanism of this research. The website ElectrifyMe aims to facilitate knowledge transfer and networking among research community involved in sustainable energy access.

6.2 Future work

Building up on the contributions of this PhD thesis, future work foreseen may be the following:

- Utilization of the ElectrifyMe website as a tool to communicate the trends and findings identified in this thesis work.
- Utilization of the ElectrifyMe website to further elaborate on trends and statistics studies on the most relevant criteria for the involved stakeholders.
- Enlargement of the scope of the database from islanded or isolated systems, many of them in developing countries, towards microgrids systems who are more and more popular in develope countires and Cities, and share many synergies with HRES as renewables or storage systems.
- Re-visit scenarios in view of disruptive technologies fostered by innovative solar photovoltaic solutions, electric vehicles deployment, and battery performance improvements.

Appendices

Appendix A

Case study inputs

The proposed case study aims to facilitate the definition of several scenarios for a stand-alone PV/Wind/Diesel/Battery system for a Telecommunication Centre in Spain.

To construct these different scenarios the HOMER energy modelling software [90] is used.

A.1 Location

The proposed project is a 2kW Telecommunication Center (ICT Center). The ICT Center is located in "Tossal de Baltasana", in the province of Tarragona. This is the geographical coordinates for the site:

- Latitud: N 41'18.536' / N 41'18'32.209" / N +41.3089470
- Longitud: E 0'59.292' / E 0'59'17.552" / E +0.98820900
- Altitude: 1202m

With this basic information of the site, it is possible to determine the availability of renewable energy resources (solar and wind) for the ICT Center.

A.1.1 Solar radiation and wind speed data

HOMER accepts hourly or monthly solar radiation and wind speed data. There are many sources for solar radiation and wind speed data but we have used two very popular: RETScreen and PVsyst.

- The RETScreen Clean Energy Project Analysis Software [142] is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free-of-charge, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs). The software (available in multiple languages) also includes product, project, hydrology and climate databases, a detailed user manual, and a case study based college/university-level training course, including an engineering e-textbook.

- PVsyst [143] is a software package for the study, sizing, simulation and data analysis of complete PV systems. Preliminary design, easy and fast tool, allowing for grid, stand-alone or pumping system pre-sizing. Upon user's requirements like energy/water needs and "Loss of load" probability, and very few other input parameters, this provides the PV-system component sizes, evaluates the monthly production and performances, and performs a preliminary economic evaluation of the PV system.

The RETScreen software provides the meteorological data for the city of Tarragona (see figure A.1)

This reference data from RETScreen is introduced in the PVsyst software that would provide the more accurate meteorological data using the basic information of the emplacement site of the ICT Center (see figure A.2). This data from the PVsyst software introduces the availability of renewable resources on the energy model.

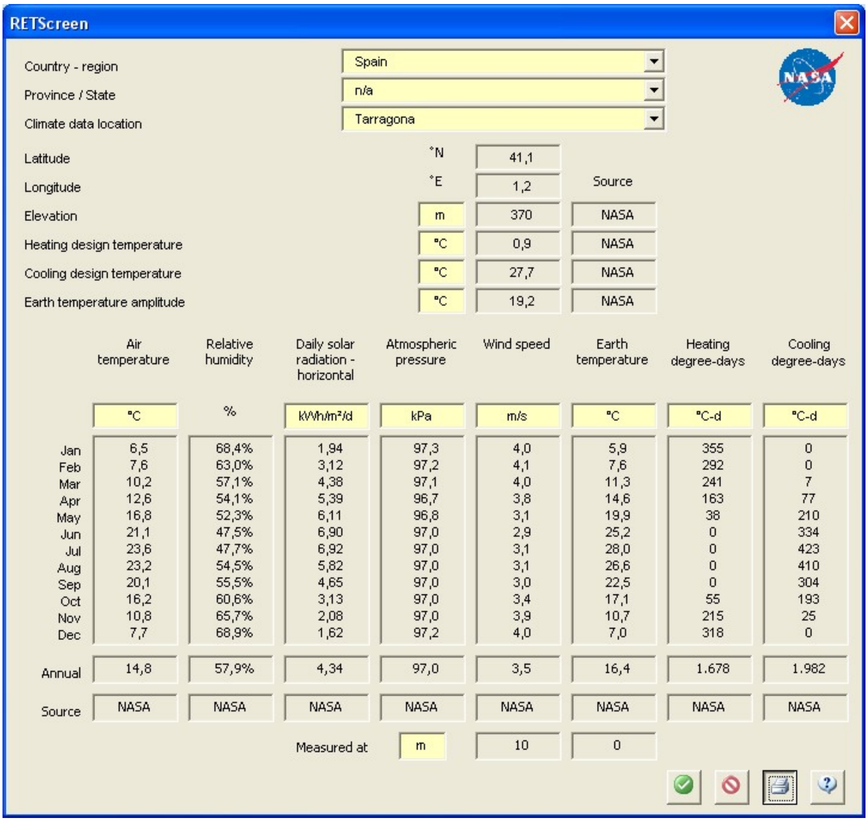
A.2 Energy model

A.2.1 PV/Wind/Diesel/Battery system

The first step to construct the different scenarios is to define the complete energy model: stand-alone PV/Wind/Diesel/Battery system. By adding element in the software HOMER we are able to construct a energy model, like the one shown in figure A.3. In order to define this system the following items are defined in HOMER: load, generation equipment, transformation equipment, resources available and other constraints of the system if necessary.

A.2.2 Load

The load for the proposed case study is for a 2kW Telecommunication Center. 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 of



RETScreen

Country - region		Spain	
Province / State		n/a	
Climate data location		Tarragona	
Latitude	°N	41,1	
Longitude	°E	1,2	Source
Elevation	m	370	NASA
Heating design temperature	°C	0,9	NASA
Cooling design temperature	°C	27,7	NASA
Earth temperature amplitude	°C	19,2	NASA

	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
Jan	6,5	68,4%	1,94	97,3	4,0	5,9	355	0
Feb	7,6	63,0%	3,12	97,2	4,1	7,6	292	0
Mar	10,2	57,1%	4,38	97,1	4,0	11,3	241	7
Apr	12,6	54,1%	5,39	96,7	3,8	14,6	163	77
May	16,8	52,3%	6,11	96,8	3,1	19,9	38	210
Jun	21,1	47,5%	6,90	97,0	2,9	25,2	0	334
Jul	23,6	47,7%	6,92	97,0	3,1	28,0	0	423
Aug	23,2	54,5%	5,82	97,0	3,1	26,6	0	410
Sep	20,1	55,5%	4,65	97,0	3,0	22,5	0	304
Oct	16,2	60,6%	3,13	97,0	3,4	17,1	55	193
Nov	10,8	65,7%	2,08	97,0	3,9	10,7	215	25
Dec	7,7	68,9%	1,62	97,2	4,0	7,0	318	0
Annual	14,8	57,9%	4,34	97,0	3,5	16,4	1.678	1.982
Source	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA
			Measured at	m	10	0		

Figure A.1: Meteorological data for the case study via RETScreen

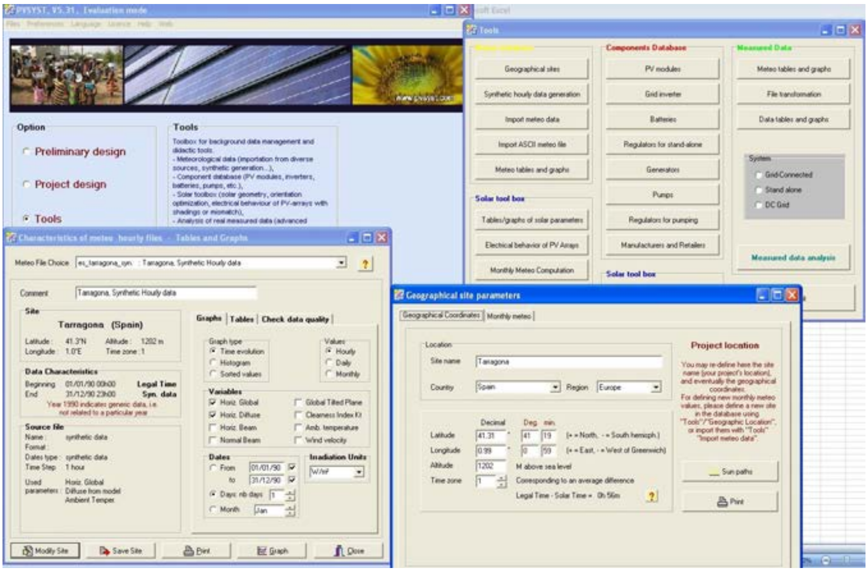


Figure A.2: Meteorological data for the case study via PVsyst

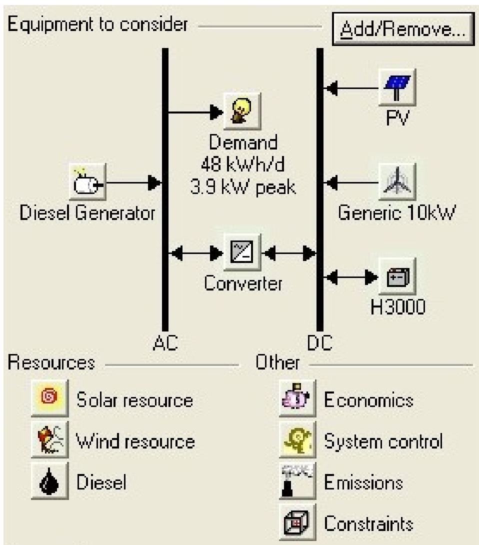


Figure A.3: Energy model for the PV/Wind/Diesel/Battery system

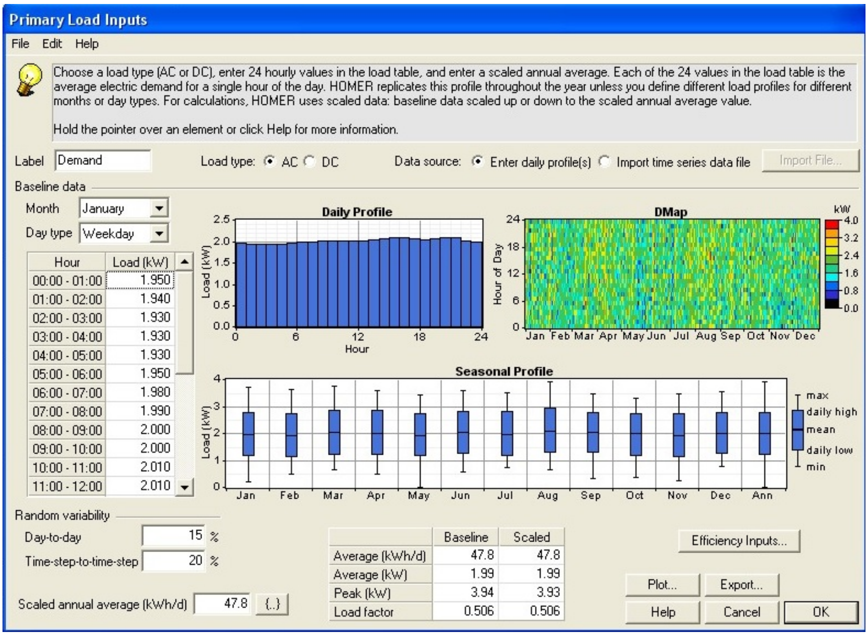


Figure A.4: Primary Load Input

electrical energy for telecommunication infrastructure and services. The basic requirements for telecommunication power systems are presented below:

- Provide uninterruptible power to critical loads. Achieved using batteries to bridge interruptions.

- Be safe to workers and the public. Achieved using relatively low voltages, current limiting and grounding

- Have long life (20 to 30 years, or more). Achieved using conservative design and planned preventive maintenance.

The primary load inputs for the case study are detailed in figure A.4.

In relation with the constraints, as far as it is a critical load, the maximum capacity shortage is 0% as indicated in figure A.5. That means the unmet load of the system would be always equal to zero and it will assure the ininterrumpibility of the supply.

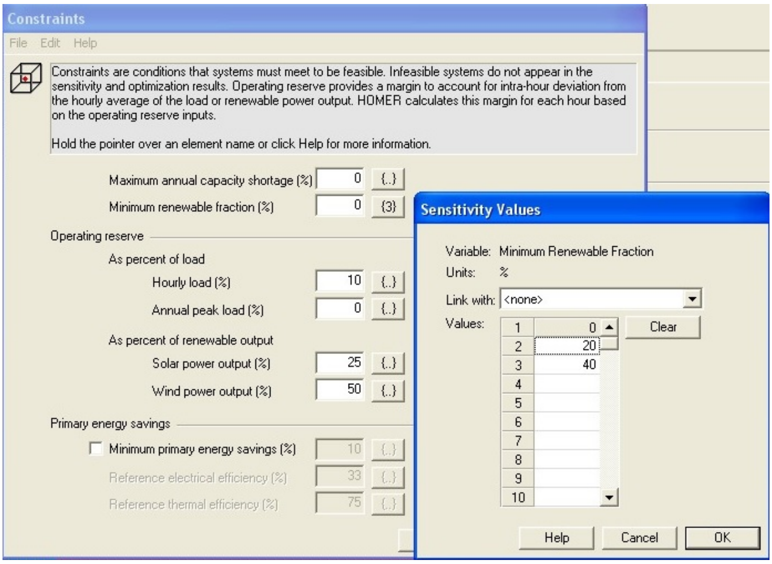


Figure A.5: Constraints

A.2.3 Renewable resources

The renewable sources inputs, for both solar and wind resources available in the location of the case study, are detailed in figure A.6 and figure A.7.

A.2.4 Fuel resources

As fuel resources, the price of the diesel in USD per liter is introduced, see figure A.8.

A.2.5 Generation and storage technology inputs

PV inputs are detailed in A.9. Wind turbine inputs are detailed in A.10. Battery inputs are detailed in A.11.

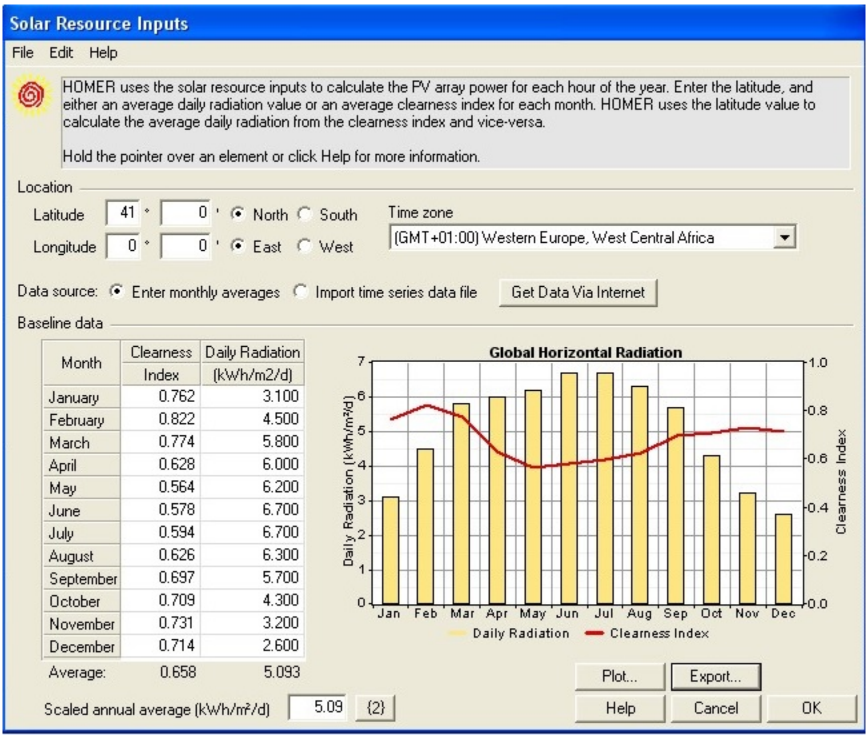


Figure A.6: Solar Resource Inputs

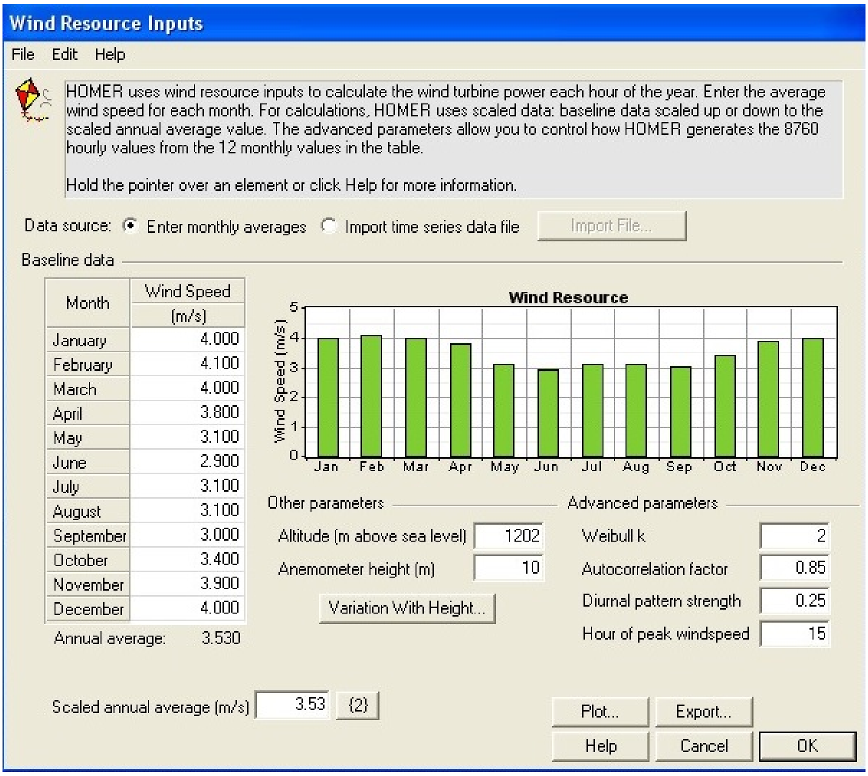


Figure A.7: Wind Resource Inputs

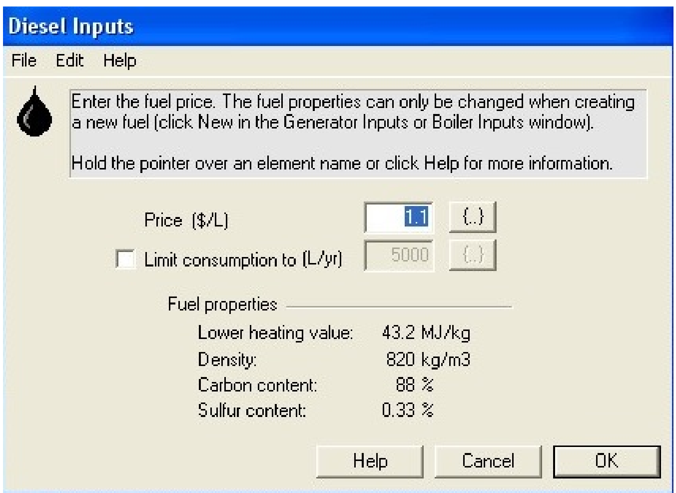


Figure A.8: Diesel Inputs

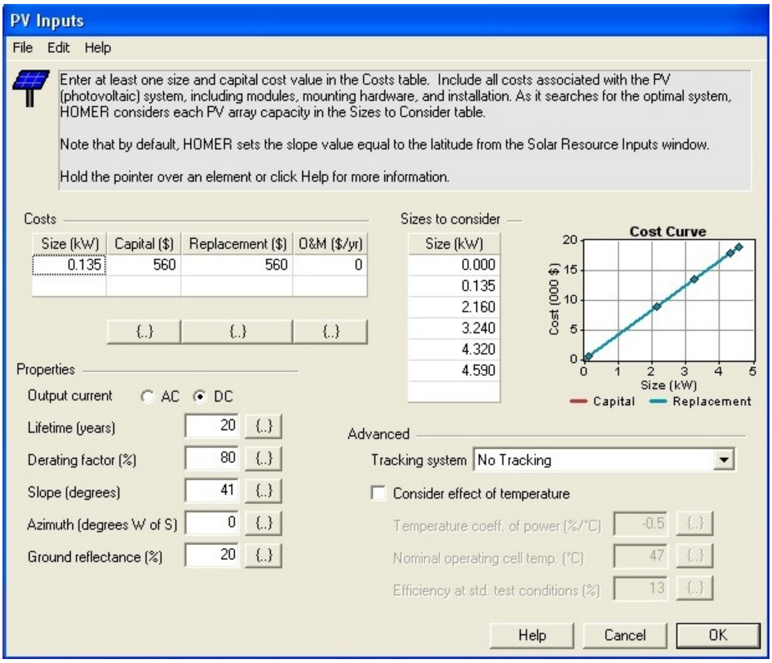


Figure A.9: PV inputs

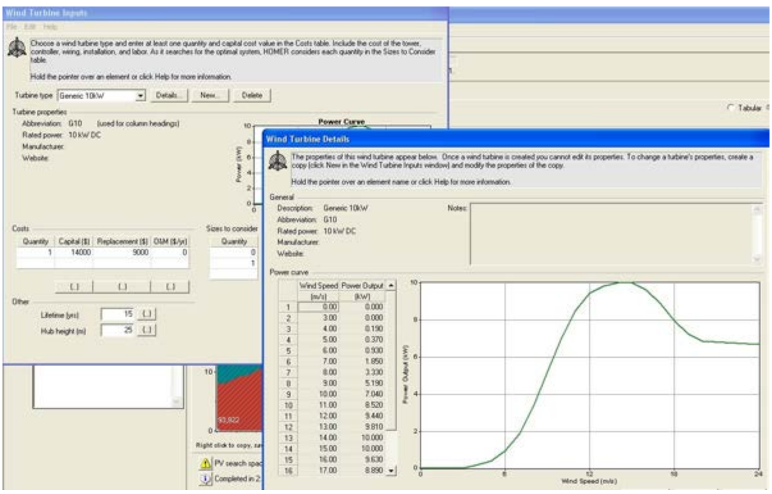


Figure A.10: Wind turbine inputs

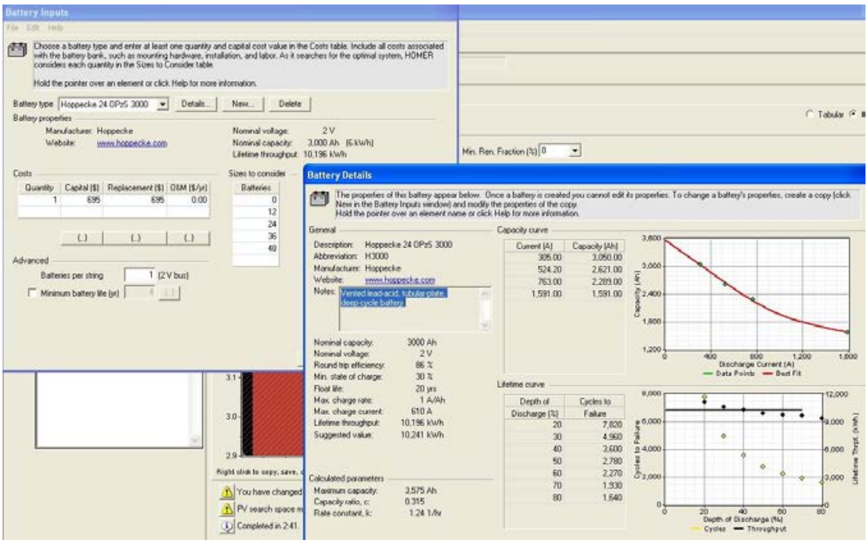


Figure A.11: Battery inputs

Appendix B

Academic Curriculum Vitae

International peer reviewed publications

M. Martínez-Díaz, R. Villafáfila-Robles, D. Montesinos-Miracle and A. Sudrià-Andreu, "Study of optimization design criteria for stand-alone hybrid renewable power systems", International Conference on Renewable Energies and Power Quality (ICREPQ13), March 2013.

M. Martínez-Díaz and X. Crusat, "The Innovation Journey: A Challenge-based Learning methodology that introduces innovation and entrepreneurship in engineering through competition and real-life challenges", IEEE Global Engineering Education Conference (IEEE EDUCON), April 2017.

Visiting scholar at Electa-ESAT (KU Leuven, Belgium) resulting in co-tutoring agreement

Name of the university and research group: KU Leuven ESAT-Electa, Belgium. Name of the person in charge of the stay: Dr. Prof. Johan Driesen. City and country: Leuven, Belgium. Aim of the stay: PhD School EIT KIC InnoEnergy programme 6-months mobility and co-tutoring agreement. Start date: 17/12/2012. End date: 30/06/2013. Duration: 6 months.

Presentations at international conferences

Authors: M. Martínez-Díaz, R. Villafáfila-Robles, D. Montesinos-Miracle and A. Sudrià-Andreu. Title of the presentation: "Stand-alone Hybrid Renewable Power Systems". Name of the conference: 1st KIC InnoEnergy Scientist Conference. Format: Poster presentation. City and country: Leuven, Belgium. Date: 6th November 2012.

Authors: M. Martínez-Díaz, R. Villafáfila-Robles, D. Montesinos-Miracle and A. Sudrià-Andreu. Title of the presentation: "Study of optimization design criteria for stand-alone hybrid renewable power systems". Name of the conference: International Conference on Renewable Energies and Power Quality (ICREPQ13). Format: Poster. City and country: Bilbao, Spain. Date: March 2013.

Authors: Mar Martínez-Díaz, Johan Driesen. Title of the presentation: "Stand-alone Hybrid Renewable Power Systems". Name of the conference: 2nd KIC InnoEnergy Scientist Conference. Format: Oral contribution. City and country: Karlsruhe, Germany. Date: 19th November 2013.

Authors: Mar Martínez-Díaz, Johan Driesen. Title of the presentation: "Hybrid Renewable Energy Systems - towards Sustainable Energy For All in 2030". Name of the conference: Niagara 2016 Symposium on Microgrids. Format: Poster. City and country: Niagara-on-the-Lake, Canada. Date: 20-21 October 2016.

Teaching

"Smart Cities & Stand-alone hybrid renewable power systems" lecture. Organising body: "820324 - GEEN - Gestió Energètica" course, EUETIB - Escola Universitària d'Enginyeria Tècnica Industrial de Barcelona de la Universitat Politècnica de Catalunya (UPC). City and country: Barcelona, Spain. Start date: 20 November 2012. End date: 20 November 2012. Duration: 2 hours.

P&D2 project-based innovation course. Research assistant with students groups working in the ALIVE & KICking project assignments. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Leuven, Belgium. Start date: February 2013. End date: June 2013. Duration: 1 semester, 3 ECTs course.

"Stand-alone Hybrid Renewable Power System" HP55 seminar. Organising body: Electa-ESAT research group KU Leuven. City and country: Leuven, Belgium. Start date: 21st June 2013. End date: 21st June 2013. Duration: 2 hours.

Smart Cities week innovation course. Co-organization and evaluation of assignments. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Leuven, Belgium. Start date: November 2013. End date: December 2013. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

P&D2 project-based innovation course. Organization and guidance of 3 groups of master students in KIC InnoEnergy innovation projects: "Mind of Power" with Triphase and "DEAL" with Ledmotive. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Leuven, Belgium. Start date: February 2014. End date: June 2014. Duration: 1 semester, 3 ECTs course.

Summer School. Organization summer course for innovation and entrepreneurship. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Antwerpen, Belgium. Start date: 29 June 2014. End date: 5 July 2014. Duration: 1 week, 3 ECTs course.

Smart Cities week innovation course. Organization and evaluation of assignments. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Barcelona, Spain. Start date: 15 November 2014. End date: 23 November 2014. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

P&D2 project-based innovation course. Teaching and guidance of 6 groups of master students in KIC InnoEnergy innovation projects. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Leuven, Belgium. Start date: February 2015. End date: June 2015. Duration: 1 semester, 3 ECTs course.

Summer School. Organization summer course for innovation and entrepreneurship. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Brussels, Belgium. Start date: 28 June 2015. End date: 4 July 2015. Duration: 1 week, 3 ECTs course.

Smart Cities week challenge-based innovation course. Organization with 10 companies and 52 students. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Barcelona, Spain. Start date: 14 November 2015. End date: 22 November 2015. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

BIZbootcamp challenge-based innovation course. Organization and guidance of groups of master students in 10 real-life challenges from companies and start-ups. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Leuven, Belgium. Start date: 26 March 2016. End date: 2 April 2016. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

"From invention to innovation" workshop. Authors: Mar Martínez-Díaz, Xavier Crusat. Organising body: Energy Now event "Energy Storage & Smart Grids". City and country: Eindhoven, The Netherlands. Date: 9th of June of 2016. Duration: 2 hours.

Entrepreneurship School challenge-based innovation course. Organization to build up 10 entrepreneurial proposals by the groups of master students in 10 real-life challenges. Organising body: Electa-ESAT research group KU Leuven - EIT InnoEnergy MSc Energy for Smart Cities. City and country: Amsterdam, The Netherlands. Start date: 26 June 2016. End date: 2 July 2016. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

Smart Cities week challenge-based innovation course. 10 companies and 28 first year students plus 10 second year students with their own innovation proposal. Organising body: Electa-ESAT research group KU Leuven- EIT InnoEnergy MSc Energy for Smart Cities. City and country: Barcelona, Spain. Start date: 12 November 2016. End date: 20 November 2016. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

BIZbootcamp challenge-based innovation course. Organization and guidance of groups of master students in the 10 real-life challenges from companies and start-ups and 10 second year students with their own innovation proposal. Organising body: Electa-ESAT research group KU Leuven- EIT InnoEnergy MSc Energy for Smart Cities. City and country: Leuven, Belgium. Start date: 12 March 2017. End date: 18 March 2017. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

Entrepreneurship School challenge-based innovation course. Organization week course to build up 10 entrepreneurial proposals and 3 start-up proposals. Organising body: Electa-ESAT research group KU Leuven- EIT InnoEnergy MSc Energy for Smart Cities. City and country: Amsterdam, The Netherlands. Start date: 2 July 2017. End date: 8 July 2017. Duration: 1 week out-of-the-classroom and online work 1 semester, 3 ECTs course.

Doctoral courses at UPC

Electricity generation from renewable sources. Organising body: ETSEIB - Doctoral degree in electrical engineering. City and country: Barcelona, Spain. Start date: October 2008. End date: January 2009. 5 ECTs course.

Operation and management of electrical power systems in a distributed environment. Organising body: ETSEIB - Doctoral degree in electrical engineering. City and country: Barcelona, Spain. Start date: February 2009. End date: June 2009. 5 ECTs course.

Power electronics: technology for renewable energies and distributed generation. Organising body: ETSEIB - Doctoral degree in electrical engineering. City and country: Barcelona, Spain. Start date: February 2009. End date: June 2009. 5 ECTs course.

Introduction to electrical engineering research. Organising body: ETSEIB - Doctoral degree in electrical engineering. City and country: Barcelona, Spain. Start date: January 2010. End date: June 2010. 10 ECTs course.

Doctoral training at KU Leuven

"Doctoral School Training course: Exploitation of research, Technology and Knowledge Transfer". Organising body: KU Leuven Research & Development (LRD) at KU Leuven. City and country: Leuven, Belgium. Start date: November 2013. End date: April 2015. Five day course spread over a period of six months.

PhD School courses and activities via EIT InnoEnergy

"Entrepreneurial Crash course: From Science to Business". Organising body: ESADE / PhD School InnoEnergy. City and country: Barcelona, Spain. Start date: September 2010. End date: September 2010. 4ECTs.

"Introductory Crash course in Entrepreneurship". Organising body: ESADE / PhD School InnoEnergy. City and country: Barcelona, Spain. Start date: September 2012. End date: September 2012. Number of hours: 4ECTs.

Workshops at the "1st Scientific conference" EIT InnoEnergy. Organising body: KU Leuven / PhD School InnoEnergy. City and country: Leuven, Belgium. Start date: November 2012. End date: November 2012. 4 ECTs.

"Renewables bootcamp". Organising body: IST / PhD School InnoEnergy. City and country: Lisbonne, Portugal. Start date: December 2012. End date: December 2012. 4ECTs.

Smart Cities Module 1 - E-mobility in Smart Cities. Organising body: KU Leuven / PhD School InnoEnergy. City and country: Leuven, Belgium. Start date: 26 January 2014. End date: 31 January 2014. 40 hours.

Energy Systems Integration 101. Organising body: KU Leuven / PhD School InnoEnergy. City and country: Leuven, Belgium. Start date: 18 May 2015. End date: 22 May 2015. 40 hours.

2015 Aalborg Microgrid Symposium. City and country: Aalborg, Denmark. Start date: 27 August 2015. End date: 28 August 2015.

Participation in research projects

Green eMotion: Development and demonstration of a unique and user-friendly framework for green electromobility in Europe. Project ID: 265499. Funding body: European Commission, FP7-TRANSPORT-2010-TREN-1. Main researcher: Heike Barlag, SIEMENS. Mar Martínez-Díaz for Fundació Institut de Recerca de l'Energia de Catalunya (IREC). Start and end date of the project: 1 March 2011 - 28 February 2015. Start and end date of the participation: August 2009 - March 2012.

KIC-ASS (Active Sub-Stations) and EV-City innovation projects. Funding body: EIT KIC InnoEnergy and partner members. Main researcher: Prof. Dr. Johan Driesen. Start and end date of the project: 2010 - 2014. Start and end date of the participation: 2009 - 2012.

UNI-SET Mobilising the research, innovation and educational capacities of European universities in the SET-Plan. Project ID: 609838. Funding body: European Commission, FP7-ENERGY Main researcher: Lidia Borrell-Damian, EUA. Start and end date of the project: 1 September 2014 - 21 December 2017. Start and end date of the participation: September 2014 - December 2017.

Organisation of awards

Master thesis competition, EIT InnoEnergy MSc Energy for Smart Cities. Role: Design, organization and member of the jury. City and country: Antwerp, Belgium. Date: 1 July 2014.

Master thesis competition, EIT InnoEnergy Master School in Energy for Smart Cities. Role: Design, organization and member of the jury. City and country: Online. Date: July 2015.

Innovation Competition 2015-2016 (3 rounds) and awarding of KI€coins within the Innovation Journey (3 challenge-based innovation courses), EIT InnoEnergy MSc Energy for Smart Cities. Role: Design, organization and member of the jury. Cities and countries: Innovation Journey 3 stops in Barcelona (Spain), Leuven (Belgium) and Amsterdam (The Netherlands). Dates: 21 November 2015, 1 April 2016, 1 July 2016.

Master thesis competition, EIT InnoEnergy Master School in Energy for Smart Cities. Role: Design, organization and jury selection. City and country: Online. Date: September 2016.

Innovation Competition 2016-2017 (3 rounds) and awarding of KI€coins within the Innovation Journey and Entrepreneurship Journey (3 challenge-based innovation courses), EIT InnoEnergy MSc Energy for Smart Cities. Role: Design, organization and jury selection. Cities and countries: Innovation Journey 3 stops in Barcelona (Spain), Leuven (Belgium) and Amsterdam (The Netherlands). Dates: 19 November 2016, 17 March 2017, 7 July 2017.

Energy expert activities

Expert evaluator for on-going FP6 and FP7 projects for the European Commission in energy low-carbon topics. Period: March - June 2014 and January - April 2015.

Technical seminar with Energy experts. Title of the contribution: ”Desarrollo energético sostenible y competitivo en las islas? Lecciones aprendidas en Proyectos Europeos”. Government Balearic Islands. Mallorca, Spain. Date: 27 June 2014.

Expert evaluator of proposals for the European Commission in 1st call Energy for low-carbon H2020 framework programme. Period: June - July 2015.

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