TECHNOLOGICAL EDUCATIONAL INSTITUTE OF WESTERN GREECE
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"RENEWABLE ENERGY SYSTEMS"

THESIS

OPTIMUM SIZING OF STAND-ALONE HYBRID PV/WIND SYSTEMS

MSc STUDENT: PAPPAS KONSTANTINOS

SUPERVISOR: KAPLANIS SOCRATES
PROFESSOR

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PROLOGUE

The present issue is the thesis conducted at the MSc course of "Renewable Energy Systems" of the Dpt of the Mechanical Engineering at the Technological Educational Institute of Western Greece. The subject deals with the simulation of a hybrid energy system constituted of photovoltaic, wind turbine and batteries as a storage bank of the produced energy and targets to the most cost-effective configuration.

The increasing use of hybrid power systems based on renewable energy, as an alternative to conventional fuels, provide in many cases reliable and economic solutions, especially in isolated areas without access to the national electricity distribution network. RES are also preferred due to the fact that their carbon footprint is considerably low or zero.

An analytic dynamic iterative algorithm is developed in this work for the calculation of the hybrid system from renewable energy at which hourly meteorological data, load demand profile and technical data of the components of the system are imported. Technical power criteria are used for the evaluation of the reliability of the system and the most cost effective solution is provided.

I am extremely grateful to my primarily supervisor Dr. Eleni Kaplanis for her valuable advices and our wonderful cooperation, and thereafter to my supervisor professor Socrates Kaplanis, for his valuable assistance, guidance and patience he has shown during all this period.

Pappas Konstantinos
July 2016

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ABSTRACT

At the present thesis it is carried out a simulation for the sizing of a hybrid power production system consisting of photovoltaics and wind turbine using batteries as a storage medium. The meteorological data that are used in the algorithm obtained from the internationally known base of Meteonorm. A dynamic analytic iterative simulation process adopted for the sizing of the hybrid energy system. Later the system is being evaluated for different electrical load consumption profiles and with different power evaluation criteria, the criteria of Loss of Load Probability (LLP) and Loss of Power Supply Probability (LPSP). Thereafter, the effect of different values of the LPSP criterion on system sizing is further investigated. Also, the algorithms that examine the effect on sizing of the hybrid system by the adoption of two different configurations, with and without of Uninterruptible Power Supply (UPS), are developed. The optimization of the previous systems is achieved by the use of the economic criteria of Levelized Cost of Energy (LCE) and Net Present Value (NPV). At last a comparison among the implemented and the graphical construction approach, proposed by Thomas Markvart, is presented.

At chapter 1 a presentation on the global energy consumption and more specifically on the commercial and residential building sectors is done. Then, the most common types of buildings according to their energy performance are analyzed. On the residential sector also it is provided a list of factors that affect energy consumption and the energy categories of house appliances.

At chapter 2 is presented the rapid change of the environment and the necessity for the implementation of the renewable energy sources and their technologies for production of different forms of energy. Furthermore, the participation of the renewable sources in energy production as well as the regulations that deal with the augmentation of their exploitation in the energy balance at several European countries are presented.

At chapter 3 provides a short description of the meteorological data and existing databases that used for hybrid renewable energy systems sizing. Also, the necessary pre-feasibility analysis for the implementation of the right combination of renewable energy systems and a review of the existing power criteria and economic evaluation criteria of the system is done. At last are presented two basic components implemented at the most autonomous hybrid systems for electricity production, which are inverter and batteries.

At chapter 4 there is a bibliographic presentation and a review of the different methods for the calculation and optimization of hybrid power systems and of several commercial available computational programs for that purposes.

At chapter 5 is a review of the various mathematical approaches used by researchers to estimate the energy produced by photovoltaics, wind turbines and

the estimation of battery capacity as a storage medium in an energy production system.

At chapter 6 are described the most common types of systems for energy management and prioritization in hybrid energy systems.

At chapter 7 there is an overview of the received weather data and the presentation of different load curves that are used in this project. Also, the two different configurations adopted for the sizing of the hybrid power system constituted of photovoltaics and wind turbine generator using batteries as storage system with the technical characteristics of the components are analyzed.

At chapter 8 a presentation of the processes of the following methodologies at the simulation algorithms for the sizing of the PV-wind hybrid energy systems is provided.

At chapter 9 are presented the results of the comparison of two different sizing methods, the iterative and the graphic construction method. Next, a presentation of the effect of the two different technical criteria (LLP and LPSP) and next of the different values of loss of power supply probability in sizing is shown. Hybrid energy system is then examined with altered load profiles and with different time intervals. Finally a comparison of the two suggested configurations, with and without UPS, for two load profiles is carried out.

In the last chapter the conclusions of the results are presented. Firstly, the comparison between the two following methods, the analytic dynamic iterative and graphical construction, reveals that only the first can provide accurate solutions. Next, LLP and LPSP power criteria are compared and an overestimating tendency of the generators with LLP it is found. Also, different load profiles and time intervals reveals that the shorter intervals and a better estimation of production and consumption provides more reliable and economic efficient systems. Finally, the comparison between the two configurations, with and without UPS, provides lower PV generator with UPS but the optimum systems occurred at all cases without UPS.

ΠΕΡΙΛΗΨΗ

Στην παρούσα διπλωματική εργασία πραγματοποιείται η προσομοίωση για την διαστασιολόγηση ενός υβριδικού συστήματος παραγωγής ισχύος το οποίο αποτελείται από φωτοβολταϊκά και ανεμογεννήτρια με την χρήση μπαταριών ως αποθηκευτικό μέσο. Τα μετεωρολογικά δεδομένα που χρησιμοποιούνται ελήφθησαν από την διεθνώς γνωστή βάση δεδομένων του Meteonorm. Μια δυναμική αναλυτική επαναληπτική διαδικασία προσομοίωσης υιοθετείται για την διαστασιολόγηση του υβριδικού ενεργειακού συστήματος. Στη συνέχεια αξιολογείται η συμπεριφορά του συστήματος για διαφορετικές καμπύλες φορτίων και με διαφορετικά κριτήρια αξιολόγησης της ισχύος, τα οποία είναι η Πιθανότητα Απώλειας Φορτίου (LLP) και η Πιθανότητα Απώλειας Παροχής Ισχύος (LPSP). Έπειτα, η επίδραση διαφορετικών τιμών της πιθανότητας απώλειας παροχής ισχύος στην διαστασιολόγηση του συστήματος ερευνάται. Επίσης, οι αλγόριθμοι οι οποίοι εξετάζουν την επίδραση δυο διαφορετικών συνδεσμολογιών, με και χωρίς την χρήση συσκευής για την αδιάλειπτη παροχή ενέργειας (UPS), αναπτύσσεται. Η βελτιστοποίηση των παραγόμενων συστημάτων πραγματοποιείται με την χρήση των οικονομικών κριτηρίων του Κλιμακούμενου Κόστους της Ενέργειας (LCE) και της Καθαρής Παρούσας Αξίας (NPV). Τέλος, μια σύγκριση μεταξύ της αναπτυσσόμενης επαναληπτικής μεθόδου και αυτής που προτάθηκε από τον Markvart παρουσιάζεται.

Στο κεφάλαιο 1 παρουσιάζεται η παγκόσμια κατανάλωση ενέργειας και ειδικότερα στον εμπορικό και οικιακό τομέα. Οι πιο συνήθεις τύποι κτηρίων βάσει της ενεργειακής τους επίδοσης αναλύονται. Στον οικιακό τομέα παρέχεται επίσης η λίστα των παραγόντων που επηρεάζουν την ενεργειακή κατανάλωση και οι ενεργειακές κατηγορίες των οικιακών συσκευών.

Στο κεφάλαιο 2 παρουσιάζεται η απότομη αλλαγή του κλίματος και η αναγκαιότητα για την υιοθέτηση των ανανεώσιμων πηγών ενέργειας και των τεχνολογιών που τις διέπουν για την παραγωγή διαφορετικών μορφών ενέργειας. Επιπλέον, τα ποσοστά συμμετοχής των ανανεώσιμων πηγών στην παραγωγή ενέργειας καθώς και κανονισμοί των χωρών της για την μεγαλύτερη εκμετάλλευσή τους στο ενεργειακό τους ισοζύγιο περιγράφονται.

Στο κεφάλαιο 3 παρέχεται μια περιγραφή των μετεωρολογικών δεδομένων που ελήφθησαν από υπάρχουσα βάση και χρησιμοποιούνται για την διαστασιολόγηση του υβριδικού συστήματος. Ακόμη, η αναγκαιότητα της ανάλυσης προ-βιωσιμότητας για την υιοθέτηση του κατάλληλου συνδυασμού ανανεώσιμων ενεργειακών συστημάτων και κριτική υπαρχουσών κριτηρίων ισχύος και οικονομικής αξιολόγησης πραγματοποιείται. Τέλος γίνεται περιγραφή δυο βασικών μερών των περισσοτέρων αυτόνομων ενεργειακών συστημάτων για την παραγωγή ηλεκτρισμού, του μετατροπέα τάσης (inverter) και των μπαταριών.

Στο κεφάλαιο 4 γίνεται βιβλιογραφική αναφορά και κριτική διαφόρων μεθόδων για τον υπολογισμό και βελτιστοποίηση των υβριδικών συστημάτων παραγωγής ισχύος καθώς και διαφόρων εμπορικά διαθέσιμων λογισμικών πακέτων για αυτό τον σκοπό.

Στο κεφάλαιο 5 γίνεται μια κριτική ποικίλων μαθηματικών προσεγγίσεων που χρησιμοποιήθηκαν από ερευνητές για την εκτίμηση της παραγόμενης ενέργειας των φωτοβολταϊκών, των ανεμογεννητριών και της χωρητικότητας των μπαταριών σαν μέσο αποθήκευσης σε ένα σύστημα παραγωγής ενέργειας.

Στο κεφάλαιο 6 περιγράφονται οι πιο κοινοί τύποι συστημάτων διαχείρισης και ιεράρχησης των γεννητριών παραγωγής ενέργειας σε ένα υβριδικό σύστημα.

Στο κεφάλαιο 7 γίνεται μια επισκόπηση των μετεωρολογικών δεδομένων που ελήφθησαν και η παρουσίαση των διαφορετικών καμπυλών φορτίου που χρησιμοποιήθηκαν σε αυτή την εργασία. Ακόμη, τα δυο διαφορετικά συστήματα που χρησιμοποιούνται για την διαστασιολόγηση του υβριδικού συστήματος παραγωγής ισχύος το οποίο αποτελείται από φωτοβολταϊκά και ανεμογεννήτρια με την χρήση μπαταριών σαν σύστημα αποθήκευσης και τα τεχνικά τους χαρακτηριστικά αναπτύσσονται.

Στο κεφάλαιο 8 αναπτύσσονται οι διαδικασίες των ακολουθούμενων μεθοδολογιών στους αλγόριθμους προσομοίωσης για την διαστασιολόγηση των Φ/Β και Α/Γ υβριδικών συστημάτων.

Στο κεφάλαιο 9 γίνεται παρουσίαση των αποτελεσμάτων της σύγκρισης των δυο διαφορετικών μεθόδων διαστασιολόγησης, της επαναληπτικής και της μεθόδου γραφικής απεικόνισης. Μετά, γίνεται παρουσίαση της επίδρασης των δυο διαφορετικών τεχνικών κριτηρίων (LLP και LPSP) και ακολούθως για διαφορετικές τιμές του LPSP, στην διαστασιολόγηση του συστήματος. Το υβριδικό σύστημα έπειτα εξετάζεται με εναλλακτικές καμπύλες φορτίου και για διαφορετικά διαστήματα προσομοίωσης. Τέλος, μια σύγκριση μεταξύ των δυο προτεινόμενων συνδεσμολογιών, με και χωρίς UPS, για δυο διαφορετικές καμπύλες φορτίου πραγματοποιείται.

Στο τελευταίο κεφάλαιο παρουσιάζονται τα συμπεράσματα των αποτελεσμάτων. Αρχικά, η σύγκριση των δυο ακολουθούμενων μεθόδων, της αναλυτικής δυναμικής επαναληπτικής και της γραφικής απεικόνισης, αποκαλύπτουν ότι μόνο η πρώτη μέθοδος μπορεί να παρέχει ακριβή αποτελέσματα. Στην συνέχεια, από την σύγκριση των δυο τεχνικών κριτηρίων για την αξιολόγηση της ισχύος, LLP και LPSP, βρέθηκε ότι το κριτήριο του LLP εμφανίζει συνεχώς αυξημένη γεννήτρια. Ακόμη, οι διαφορετικές καμπύλες φορτίων και τα διαφορετικά διαστήματα προσομοίωσης αποκάλυψαν ότι, μικρότερα διαστήματα με καλύτερη εκτίμηση για το ταίριασμα της παραγωγής με την κατανάλωση δημιουργεί πιο αξιόπιστα και οικονομικά αποδοτικά συστήματα. Τέλος, από την σύγκριση των δυο συνδεσμολογιών, με και χωρίς UPS, τα μικρότερα συστήματα παράγονται με την χρήση του UPS ενώ τα βέλτιστα συστήματα προέκυψαν σε όλες τις περιπτώσεις όταν δεν υπήρχε το UPS.

CONTENTS

INTRODUCTION

Global concern for greenhouse emissions by human activity and its impact on the environment enhanced the research efforts to inform people for the consequences on Earth. Carbon dioxide and other warming emission gases leads to trap heat and drive up the planet's temperature, and create significant and harmful impacts on our health, environment, and on our climate. International Panel on Climate Change[1] (IPCC) reported that warming emissions associated with renewable energy, counting of manufacturing, installation, operation, maintenance, dismantling and decommissioning, are minimal.

In general, renewable energy is defined as the energy that obtained from natural resources and replenishes also in natural ways, for example sunlight, wind, rain, tides, waves and geothermal. Common use of renewable energy is for electricity generation, air or water heating and cooling, transportation, rural and etc. The transition from fossil fuel energy generation to new renewable energy can directly reduce atmospheric carbon footprint [1,2]. Carbon footprint is called the total greenhouse gas emissions caused by the procedure of production, transportation and etc. and expressed as CO_2e. Another term often used is the energy footprint which is a measure of land required to absorb the CO_2 emissions.

Foremost advantage of the use of renewable energy systems constitutes that is sustainable and never runs out. Also, these systems require less maintenance and the operation costs are relatively low due to the natural sources as working fuels and the production of carbon and chemical pollutants has minimal impact to the environment. Economic benefits should be mentioned, as most of the accomplished projects, located away from urban centers and suburbs of the capital cities, and may be increase the use of local services and even the deployment of tourism. But there are some disadvantages with the use of environmental friendly systems such as the larger size of the required generators for a specific amount of energy. The randomness of the energy sources, when talking for renewable, constitutes a great challenge for researchers and construction companies to achieve the reliability of supply.

On the other hand, renewable energy sources are less competitive in comparison to conventional, due to their uncertainty and intermittent nature of resources [3], and also with high initial cost. To prevail this and provide an economic, reliable and sustained energy production a modified configuration that integrate different renewable technologies in a hybrid system is often verified. Hybrid combination provides a better utilization of the characteristics of each

[1] http://www.ipcc.ch/report/ar5/wg2/docs/WGIIAR5_SPM_Top_Level_Findings.pdf

source and improves system performance and efficiency [4]. Energy efficiency is inseparable related to energy consumption and increasing of efficiency leads to reduction of consumption, if appropriate measures for discouraging the occurrence of rebound effects are delivered. Nowadays, the evolution of technologies by meaning of the adoption of new materials and the improvement of the efficiency of the overall system leads to a decline in the cost of renewable systems.

The adoption of new renewable technologies for the energy production on residential building sector is very important and should be carefully chosen on the design phase [5]. Due to the time extended storage difficulty of electric energy and higher costs, a matching between the load demand and production is necessary. To achieve that, several factors that define the profile of energy consumption like the diversity of households, number and energy behavior of occupants, employment status and others, should be considered. Therefore, the utilization of energy, by means of less portions of useless energy and deficit energy, must provide the appropriate amounts with the lowest cost.

In remote places where the access to public utility network is unattainable or the financial burden is high hybrid energy systems with renewable or/and conventional generators are preferred [6]. For such systems in order to be energy sufficient, the evaluation of the potential of the natural sources for the site is essential, and the choice of the appropriate conventional source is necessary. The most suitable mix of generators is provided under the economic optimization of the obtained systems.

An integrated energy design of a building embodies new, efficient and environmental friendly technologies. Crucial for a building is the orientation (mostly applicable in remote areas), spatial arrangement of the rooms, and the right choice of the materials of the building shell. If these factors are sensibly considered a reduction of the energy demand can be achieved, to procure thermal, humidity, acoustic and optical comfort, and consequently a lower production system will be delivered. Nowadays, employment of intelligent systems for energy management contributes to an improved energy exploitation by reducing high portions of excess energy, whenever occur and is possible, and by lowering peak load demands or even avoiding cases where produced energy deficiency might lead to a system failure.

National policies [7] and other constraints can motivate or discourage investors to use renewable energy systems. Hence, despite of the potential of the knowledge for the sources at the site of interest, furthermore knowledge of laws from investor, and obligations of government to improve understanding and the economic benefits by adopting RES are listed below:

- Potential and optimal exploitation of renewable energy sources.
- More environmental friendly technologies.
- National policies and motivations for the use of renewable systems that can possibly combine more than one energy sources and at least one renewable.

- Increasing the share of RES technologies for electricity production in the national utility network.
- Knowledge of the overall daily consumption, the variation in shorter time intervals and the peak loads for the specific site.
- Economic aspects for the investment installation, operation, maintenance and replacement parts for the life span of the system under system reliability.

As solar and wind energy are abundant in many sites in Greece, for the purpose of this thesis a hybrid system with PVs, wind turbine and storage banks are considered for a dwell at Rhodos island and validated in terms of power and economics. Two different techniques an analytic dynamic iterative programming approach and a graphical construction method are used and compared. The purpose of this comparison is to provide a better point of view between a detailed calculation method and a simpler estimation for everyday use. Benefits and handicaps are presented.

After, the analytic iterative method is implemented for supplementary investigation under different time increments, power constraints, levels of autonomy and finally two different schematic provisions of hybrid system parts. All these are optimized with the economic constraints of LCE and NPV.

1 ON THE ENERGY CONSUMPTION

Due to climate changes and growing presence of diseases related to the contamination of air, land, and water it is started a great worldwide effort for conventional energy systems replacement. The use of renewable energy substantially increased the last two decades and small-medium and large scale have been designed or implemented from organizations and nations to motivate people's awareness on the subject [8]. The evolution of technology in this field exhibits an upward progress and many innovative applications become more and more popular.

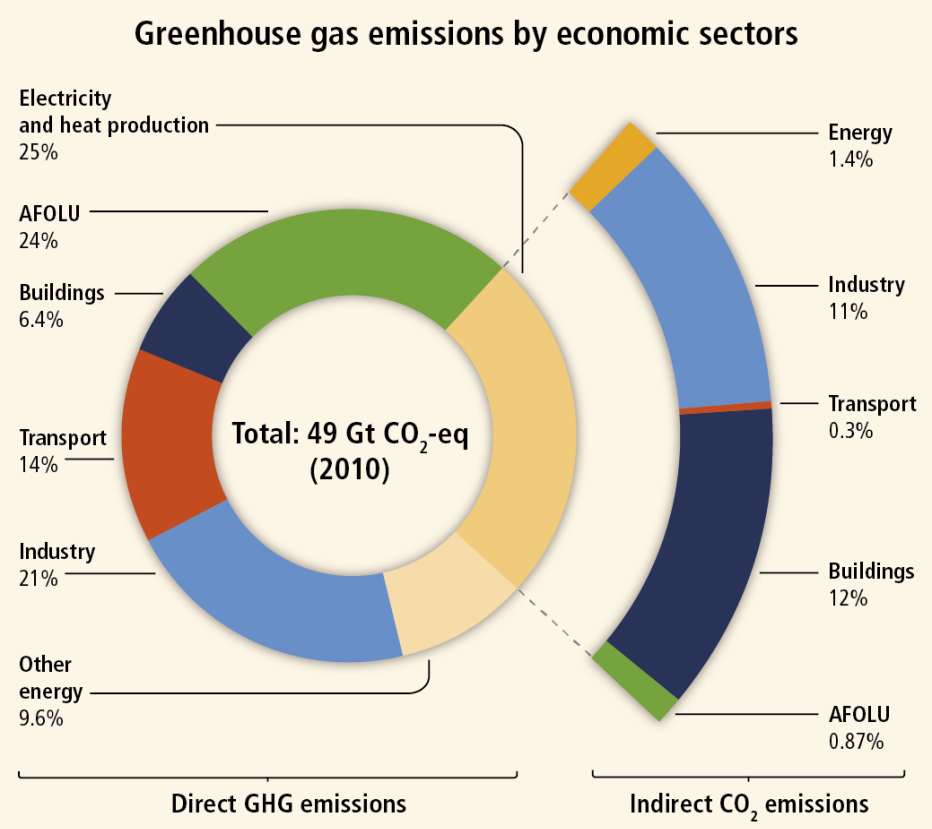


Figure 1-1 The graph above shows the proportion of greenhouse gas (GHG) (in % of total anthropogenic GHC emissions) emissions by economic sectors of the global economy in 2010. The emissions data from Agriculture, Forestry and Other Land Use (AFOLU) includes land-based CO2 emissions from forest fires, peat fires and peat decay. (source: IPCC Climate Change 2014 Mitigation of Climate Change AR5/WG3).

The annual GHG emissions caused by humanity have increased by 10 Gt CO_2 equivalents from 2000 till 2010, and it is found that comes from energy

supply 47%, industry 30%, transport 11% and buildings sectors 3%. As for indirect emissions buildings and industry sectors contribution raises[2].

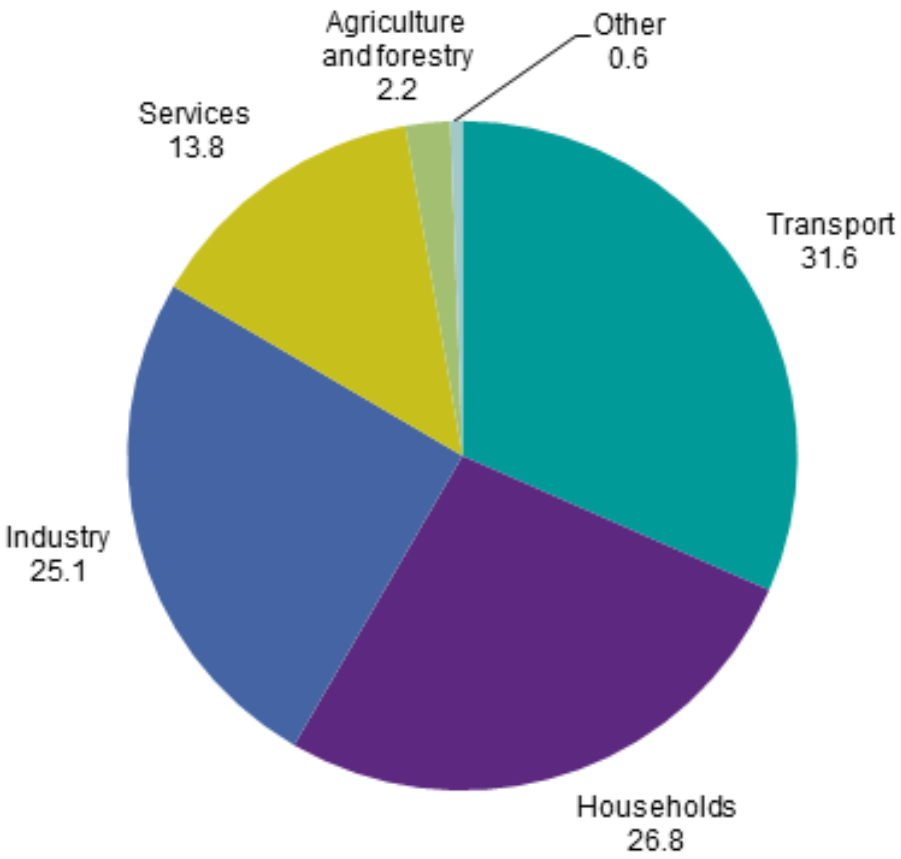


Figure 1-2 Final energy consumption, EU28, 2013 (% of total, based on tons of oil equivalent). (source: EUROSTAT[3])

Eurostat provided the results of a research about the final end use of energy for EU-28 in 2013 and revealed three prevailing categories: transport with 31.6%, households 26.8%, and industry 25.1% (figure 1-2). For the period 1990-2012 the gross inland consumption of energy remained almost the same for EU-28, with some variations whose highest value appeared at 2006. It is astonishing the fact that energy mix in Europe presented a gradual decline of petroleum products and solid fuels from 65.1% to 50.6%, during the same period (figure 1-3). This trend reflecting a move away from polluting fuels and is reinforced by the datum that renewables have almost tripled their contribution from 4.3% at 1990 to 11.8% at 2013.

[2] http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf

[3] http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Final_energy_consumption,_EU-28,_2013_(%C2%B9)_(%25_of_total,_based_on_tonnes_of_oil_equivalent)_YB15.png

All these leads to a competitive low carbon economy for EU [4]. This policy aims to establish a framework to promote energy efficiency and promotes actions to implement from each member state under the indicative national energy efficiency targets for 2020. Some of these actions are: promotion of the role of public sector and the obligation to accelerate the refurbishment rate of the public sector building stock, start of the renovation process in private sector, improvement of the efficiency of appliances, advance of the heat and power generation efficiency, measures for more efficient equipment for industry and improved information provision for small and medium enterprises, and finally focus on the rumor of smart grids and smart meters so end-users could optimize their energy behavior.

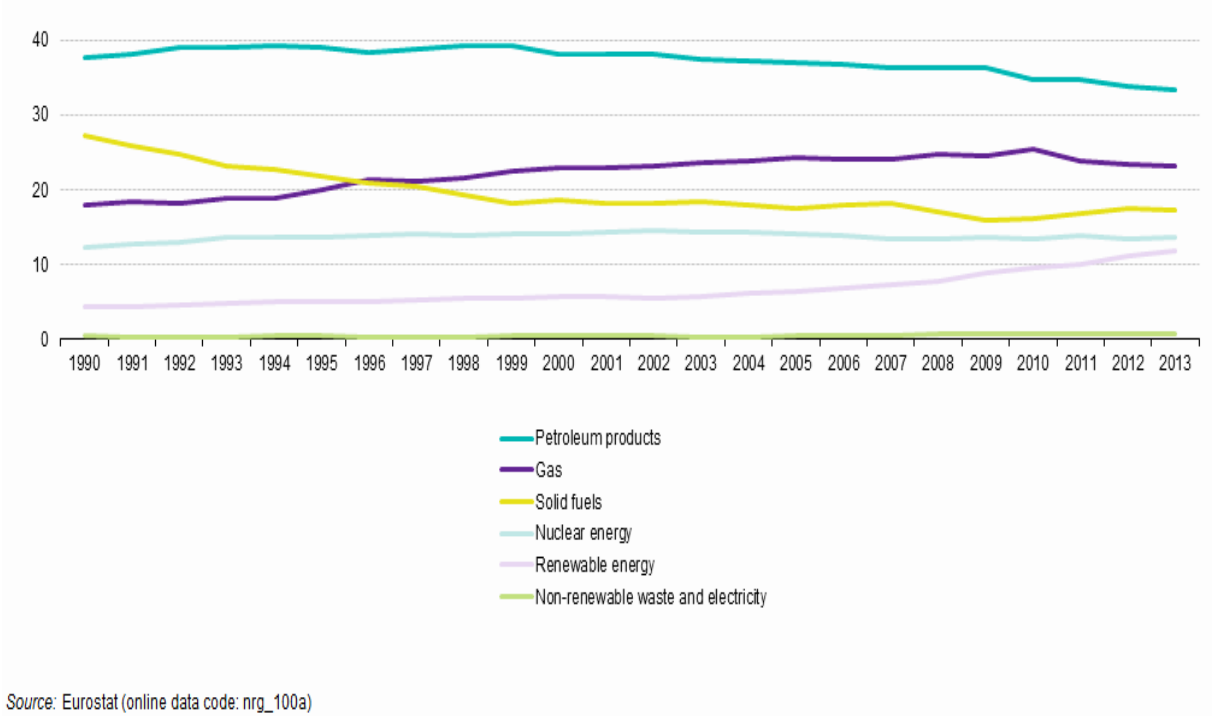


Figure 1-3: The gross inland consumption, EU-28, 1990-2013 (% of total consumption). (Source: Eurostat)

1.1 TRENDS IN WORLD ENERGY CONSUMPTION

There is widespread popular support for using solar and wind energy for electric energy production and zero carbon dioxide emissions during operation. Barriers to this trend is the initial capital investment, low efficiency of the generators and the intermittent nature of the resources. Constant progress of technology and implementing measures by governments to enhance the

[4] http://www.cbss.org/wp-content/uploads/2012/12/EU-Low-Carbon-Road-Map-2050.pdf

integration of clean technology have almost eliminated the hesitation and insecurity of the people. By many researchers are proposed systems for energy production with co-generation, two or more energy sources either renewable or conventional, is used with a backup system, like batteries bank or fuel cells, it can provide fully autonomy for example to a remote household.

The Energy Information Administration (EIA) of United States estimated in 2013 that around 11% of world energy consumption originates from renewable sources (wind, solar, biomass, biofuels, hydropower and geothermal) with a prognosis of 15% for 2040 (figure 1-4).

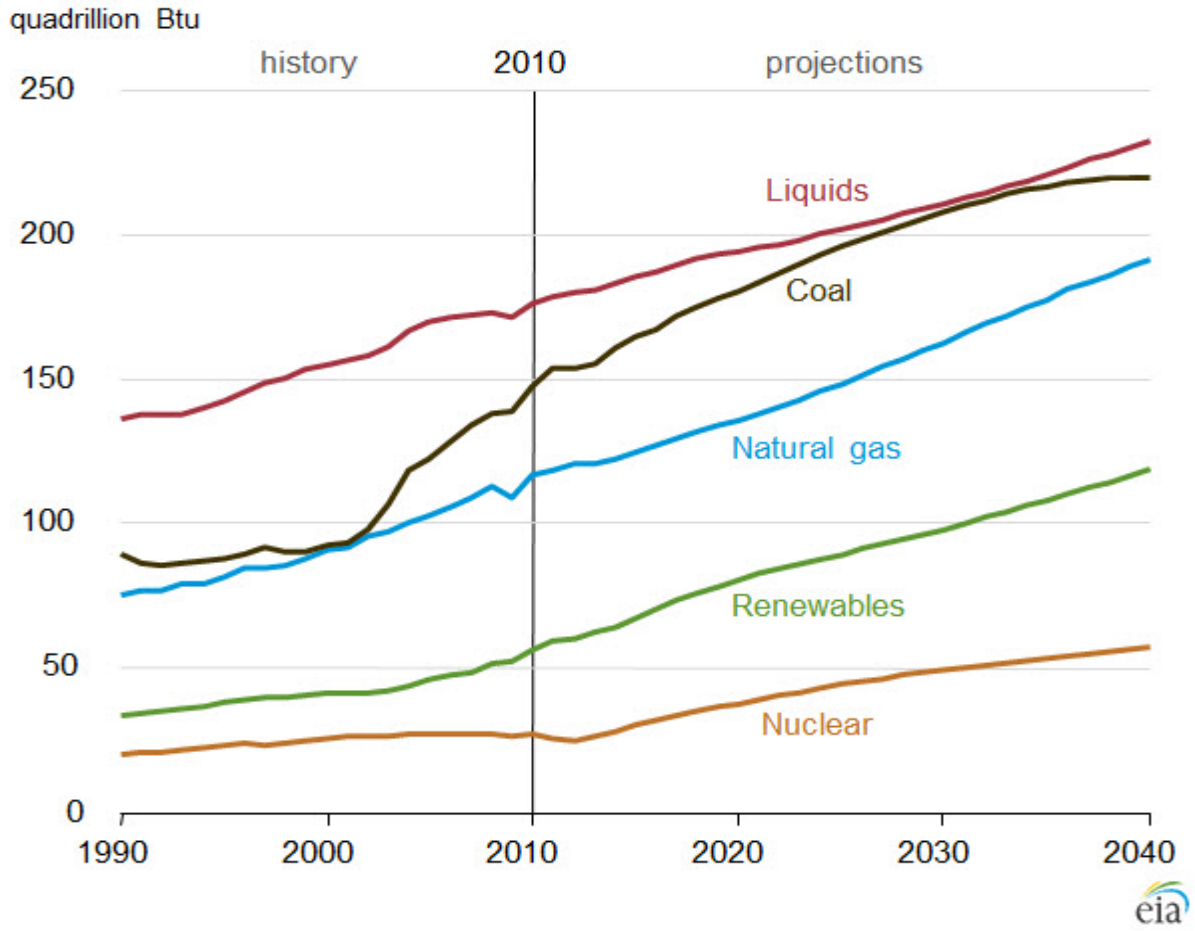


Figure 1-4 World energy consumption by fuel type 1990-2040 (source: Energy Information Administration (EIA), International Energy Outlook 2013[5]).

World residential energy increases by 1.5% per annual in the reference projection case of 2040 (International Energy Outlook_IEO2013_EIA), with the highest growth in residential energy consumption in countries of non-OECD (Organization for Economic Cooperation and Development members) where economic growth drags standards of living and increases energy demands. In commercial energy it is anticipated a growth of 1.8% for the same period. Again non-OECD nations share is the highest, about 3.2%, while for OECD members is

[5] http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf

estimated to be 0.9%. Similarly at industrial sector the energy demand grows over 30% in the reference case worldwide and the share of OECD members will be 0.6% per year, as they becoming from manufacturing to service economies, and non-OECD countries appear to have a growth of 1.8% because of the intense industrialization.

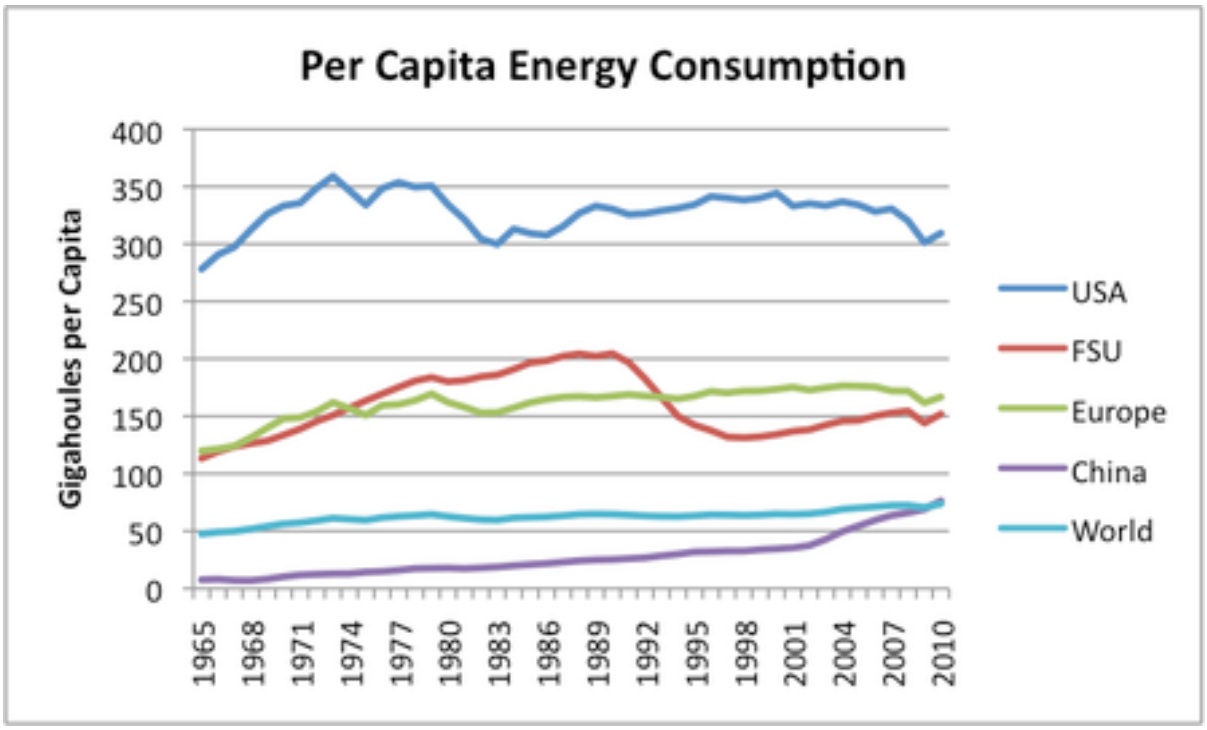


Figure 1-5 Data on energy consumption per Capita GJ/year (Source: S. Kaplanis, 8th Egeenergy Conference Afyon Kocatepe, 11-13 May 2016)

The variation of the energy patterns differentiates from 1965 to 2010 strongly in cases like Former Soviet Union (FSU). Europe's energy consumption follows world's pattern which is slightly increased. But China found to have an abruptly increase at last decade. This might be due to Kyoto protocol (1997) encouraging countries to reduce CO_2 emissions, but didn't discourage from importing products from other countries using coal as their primary fuel for electricity.

1.2 ON THE ENERGY CONSUMPTION IN BUILDINGS

Building sector exhibits high rates of energy consumption in total. At United States it is found that this sector consumes close to 40% of the total energy from all sources and 70% of the produced electricity. The target for new commercial buildings is to reduce the energy demand over 80% in the fight against global climate change. New cost effective technologies must be imported for ultra-efficient buildings become commonplace.

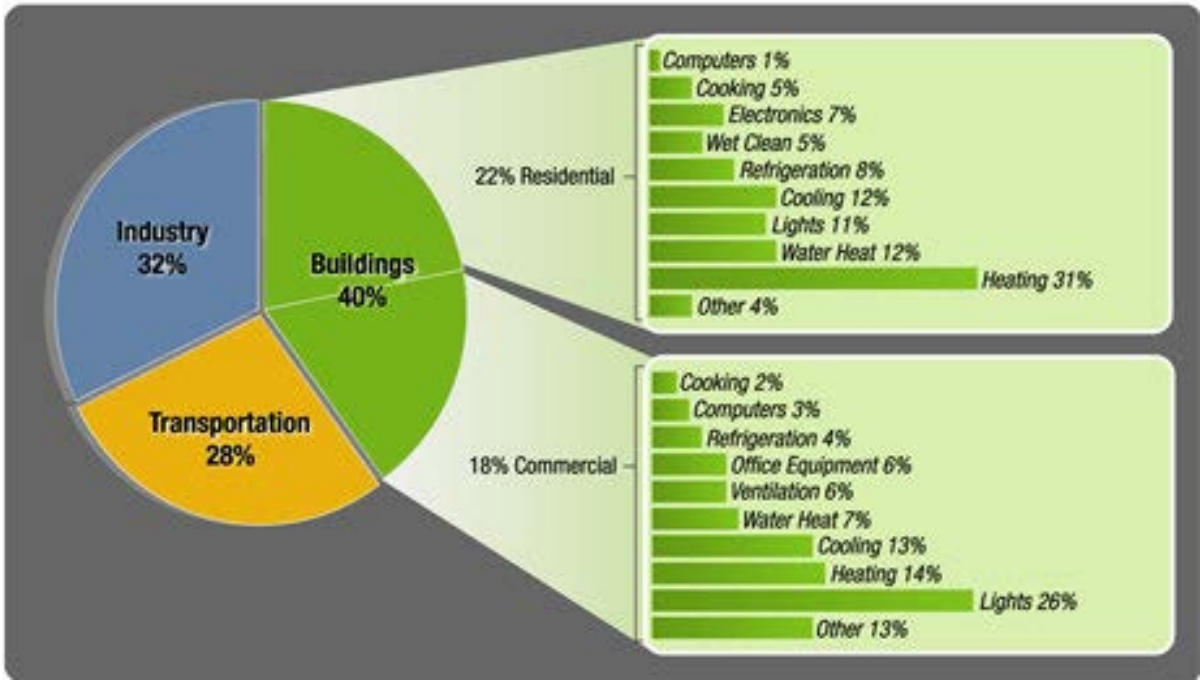


Figure 1-6 Total energy consumption at U.S.A. by sector, 2009. Buildings account 40% of the total energy produced. (source: Lawrence Berkley National Laboratory[6])

Emissions of CO_2 from building sector (commercial and residential) can largely be traced to energy use in buildings, including direct emissions and end-use electricity consumption. Diverse factors define how much energy buildings consume, meaning size of the building, design and materials, the kind of lighting installed appliances and others. Residential and commercial buildings account for 5.6% and 5.4% of total greenhouse emissions in the U.S. The major amount of direct greenhouse gas emissions for residential buildings comes from the combustion of fossil fuels, primarily heating and cooking.

For both sectors, commercial and residential, the energy used for heating and cooling purposes arises at 43% and 33% (figure 1-6), respectively. These are fairly sensitive to weather conditions every year. More than a quarter of primary energy consumed is for lighting in commercial and 11% at residential buildings.

For Europe building sector is responsible for 40% of energy consumption and 36% of CO_2 emissions. New buildings in the E.U. require 3-5 liters less than older (total 25 liter at average) one per square meter per year. Current status of buildings age is over 50 years old almost 35% of the total recorded in EU. Improvement of energy efficiency can reduce the energy consumption by 5-6% and CO2 emissions close to 5%[7].

[6] http://eetd.lbl.gov/newsletter/nl29/

[7] https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

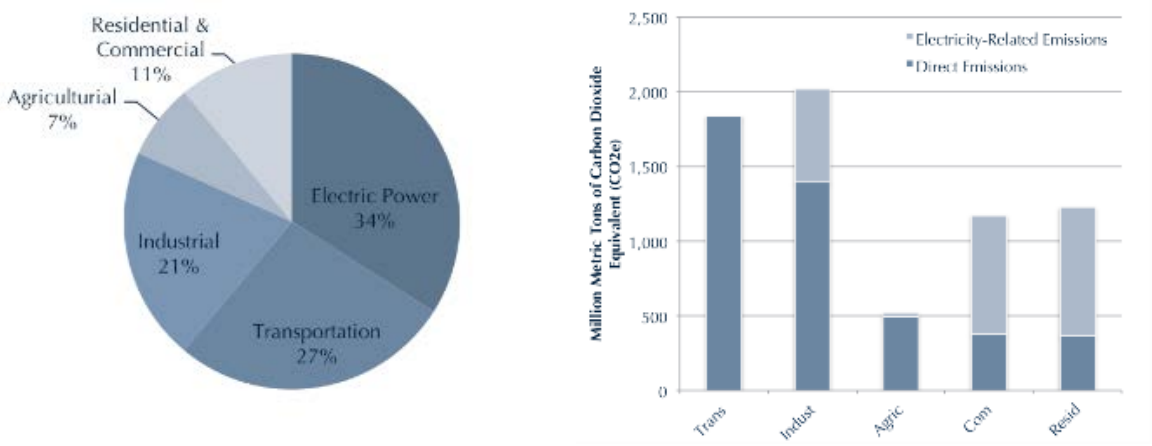


Figure 1-7 Greenhouse gas emissions by sector in USA. (Source: EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010, Table ES-7, 2012 and Table 2-14, 2012[8])

1.3 TYPES OF ENERGY BUILDINGS

Buildings are separated in four basic types; domestic, commercial, public and industrial. The domestic sector requires the higher energy amounts and it is a crucial problem for many countries that are obligated to reduce conventional resources participation. Hence, in the structure of the policies for national use of energy, clean environment, quality of life, thermal comfort and optical comfort new concepts are proposed to achieve those standards. Hence,

- Bioclimatic Buildings [9]
- Zero Energy Buildings [10]
- Intelligent Energy Buildings [11]

have been studied for the integration of new technologies and renewable for indoors comfort and high quality services with the perspective of improving the energy efficiency is great motivation for researchers and construction companies. In some cases the built-in technology is capable to provide information or even the prediction of solar radiation, where a make decision system could manage the operation of the appliances in the most cost effective way. Self-sufficiency is the goal for future houses and energy generation systems like solar thermal panels, PV modules, and small wind turbines with a storage system have already many applications, especially in rural and remote areas.

Bioclimatic design takes advantage of the site characteristics (climate, vegetation, topography and geology of the soil) in order to minimize the energy needs of the building and generate a comfortable environment (optic, thermal, humidity, acoustic) adjusted to the needs and lifestyle of the inhabitants. These buildings are carefully positioned and oriented at the landscape as well as the interior distribution to profit as much as possible of the solar gains and without

[8] https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html

interfering with summer comfort. Materials that used on building shell and openings are carefully chosen to minimize undesired transfer of energy inside or at the environment, with high energy content.

Zero energy buildings (ZEB) commonly are defined as those that the annual loads demand is produced by renewable technologies, and thus reducing conventional energy in the building sector. Other definitions that may found in literature are [12]:

- Net Zero Site Energy, A site ZEB, provides at minimum the power required for the loads in a year, when accounted for at the site.
- Net Zero Source Energy: A source ZEB, produced energy is equal or greater than the annual energy demand, when accounted for at the source. Source energy refers to the initial energy consumed either to generate or/and to deliver the energy to the site. For a building the total imported and exported energy is multiplied by a site-to-source conversion multipliers.
- Net Zero Energy Emissions: A net-zero emissions building, encloses the in-equality of the produced emissions-free renewable energy being at least equal as it uses to the emissions-producing energy sources.
- Nearly Zero Energy Buildings: A building that has very high energy performance and should be covered to very significant extent by energy from renewable sources, including renewable energy produced on-site or nearby.

Another action for the reduction of energy consumption is the use of more efficient and low energy consumption appliances. On the way towards to ZEBs there are a number of advantages concerning environmental impacts, lower costs of operation and maintenance, improved elasticity to power outages and natural disasters, and higher level of energy security. Nowadays, government agencies of all EU countries are beginning to move in a step-by-step procedure towards to ZEBs, in response to regulatory mandates.

Information of technology is adapted on buildings to automatically detect changes either power output of the integrated generators or occupants needs and react automatically or make the data available to the decision maker e.g. occupant of a household to decide. These buildings are called Intelligent Energy Buildings (IEB) or Smart Energy Buildings (SEB). The key function of intelligent energy management are energy information, fault detection and diagnostics (FDD), and measurement and verification of savings. Energy information is a dashboard illustrating data like energy production by integrated power systems, load profile analysis, energy usage and others. FDD function is useful by quick identification of operational and inefficiencies problems, and provide sustain high performance. As for measurement and verification of savings often used in projects to validate the investment and determine the payment to the energy service provider, on grid system.

In the 21st century, power production, distribution and demand tend to interconnect with a more intelligent manner. Locally microgrids are designed, and in larger scale smart grids. They are based on information and telecommunication technologies that provide information about load demands and energy production and may offer remote control whenever is asked for. Some of the benefits of these systems is the easier choice of the energy provider and in energy efficiency on the electricity grid and in the energy for users if it's provided from renewable.

Figure 1-8 Intelligent Energy Building (test cell), at Renewable Energy Sources & Systems Laboratory, of technological educational institute of western Greece, Patra.

A test cell of an intelligent energy building is installed at the Technological and Educational Institute (TEI) of western Greece, Patra (figure 1-8). The objectives of this cell is the evaluation of thermal behavior of the building and for the production of domestic hot water (DHW) and electric power. DHW is provided by two integrated solar thermal panels, one at the roof and one at the south facing façade. PV panels were installed at the roof also, in order to provide the appropriate electricity to the components of the system, like electro valves, water pumps for the underfloor heating circulation and for DHW flow (solar panels-water tank-consumption) and etc. The results are stored at the data logger which provides useful information of the complex behavior of a building at real scale condition.

1.4 FACTORS AFFECTING LOAD CONSUMPTION IN DWELLINGS

Load profile is a graph of the variation of electrical loads versus time, and as a term designates the summary of different procedures of data. So, it can provide demand or consumption information. Also it can refer to derived data like regression and profile coefficients. All these together characterize the pattern of electricity usage of a sector of electric energy customers. The settlement period is derived by load profile and provides the shape of usage during a day or year as the average values of different profiles.

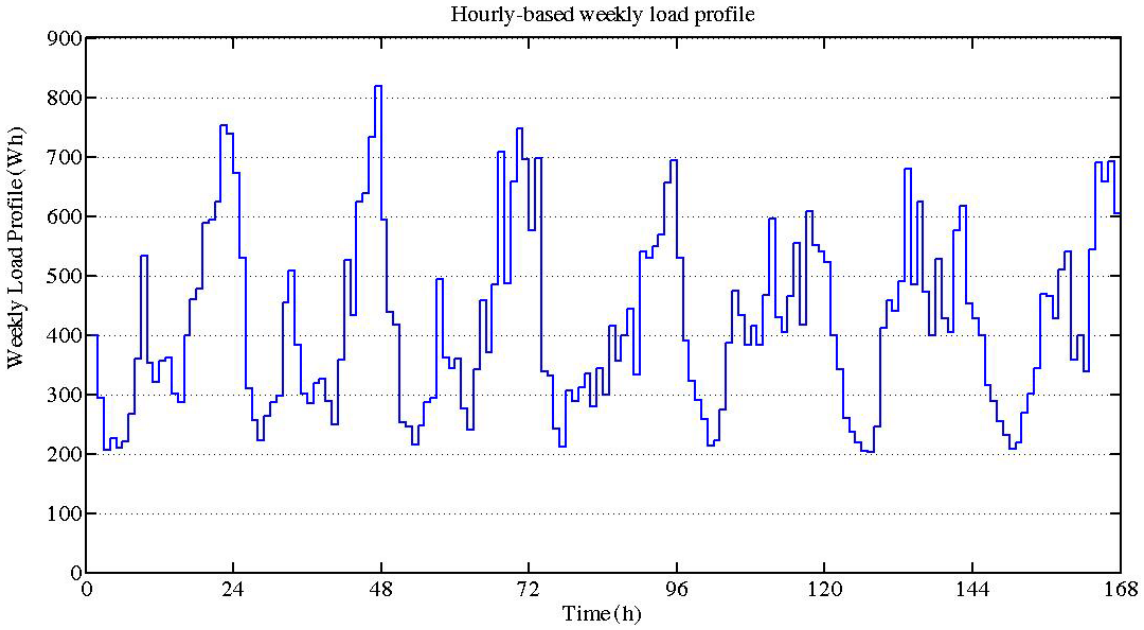


Figure 1-9 A sample of a hourly-based weekly load profile that shows the daily pattern of electricity demand in Wh for a week, at hourly increments.

In general a household consumes energy for space heating/cooling, water heating, lightning, cooking, multimedia devices, electrical appliances and other end uses.

For the appropriate sizing of the energy production system a profile of loads consumption in the household should be provided. The randomness of this can be restricted in the limits of the residents' habits. Different settlement periods of time are used in many researches, as for hourly, daily [20, 55]. Shortest time intervals provide more accurate solutions and better evaluation of the system. Since it's difficult to compel customers to take part in load research sampling, in some cases incentive payment is offered. Qualified equipment and technical staff is used for data recording in such researches.

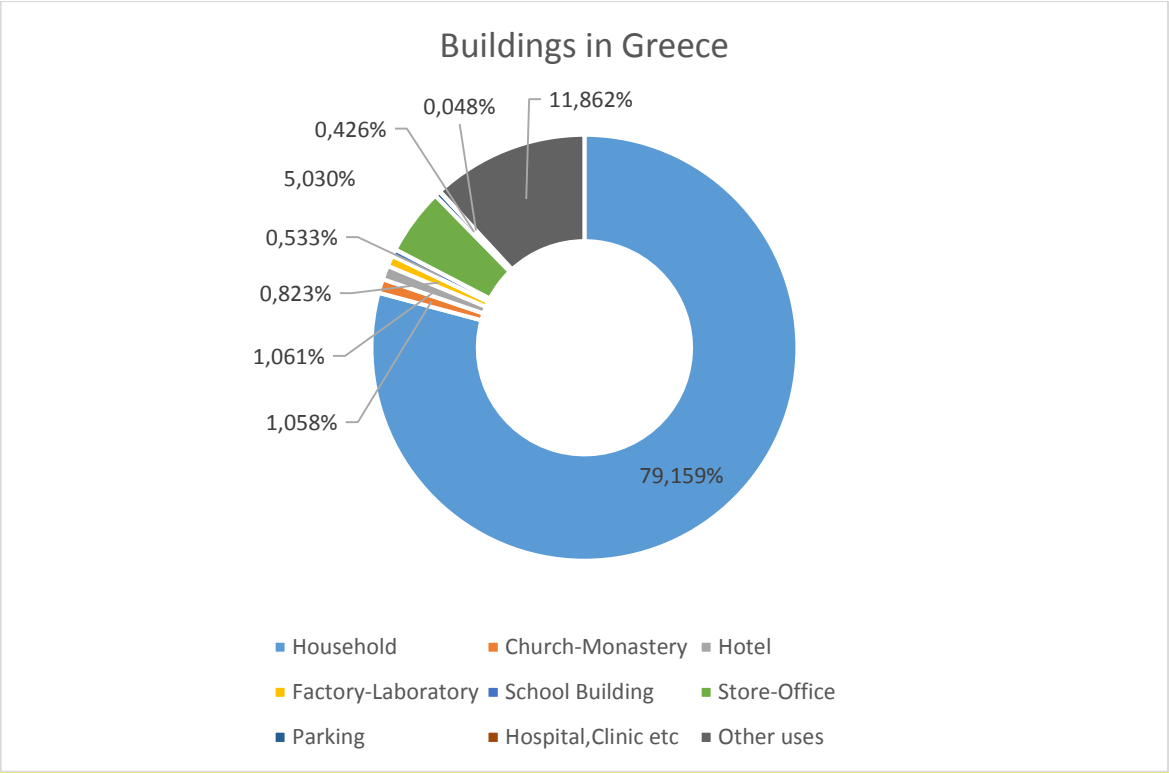


Figure 1-10 Buildings distribution by use in Greece (source: ELSTAT, MAY 2015)

Dwellings load consumption is modelled by various approaches, each one with its strengths and weaknesses. All these have been consolidated in three mainly categories of statistical/regression, engineering and neural network approaches. Engineering and neural networks are considered to be “bottom up” models and statistical/regression can be considered to be either “bottom up” or “top down”. At top down models, collected data from national energy statistics, gross domestic products and population figures and other sources are used in order to produce relationships between determinants and load consumption. Bottom up method data derived at a discrete household and relationships between household characteristics and electricity use are obtained.

Statistical/regression methods require a large dataset of real data and provide a good knowledge of electricity consumption shapes. Engineering models create electricity patterns and exploiting information like appliance ratings or end-user characteristics without using any historical data of load consumption. At last, neural networks takes a variant number of input parameters that affect load consumption and considers interaction between these parameters. It is a self-training method [13].

Rory V. Jones et al [14] investigated the effects of different factors namely socio-economic factors, dwelling factors and appliance factors on residential buildings energy consumption. For each factor several subgroups were considered and evaluated and presented here in Table 1-1.

Table 1-1 Factors with their sub-categories that effect electricity energy consumption in dwellings.

	Factors	Subgroups
1	Socio-economic	• Number of occupants • Family composition • Age of household responsible person (HRP) • Employment status of HRP • Educational level of HRP • Socio-economic classification of HRP • Tenure type • Household income • Disposable income
2	Dwelling	• Dwelling type • Dwelling age • Number of rooms • Number of bedrooms • Number of floors • Floor Area • Existence of electric heating, ventilating and air-conditioning devices/systems • Electric water heating systems • Low-energy lighting systems
3	Appliance	• Number of appliances • Ownership of IT equipment • Ownership of entertainment devices • Ownership of heating, ventilating and air conditioning (HVAC) appliances • Ownership of cooking appliances • Ownership of refrigerators/freezers • Ownership of washing machines • Ownership of laundry machines • Ownership of cleaning appliances • Ownership of hygiene and leisure devices

The correlation between the duration and the frequency of use of washing machines and electricity demand was studied by Bedir et al. [15] for homes in Dutch and it was found significant positive. Additionally, Sanquist et al. [16] found a relationship between the number of occupants and the frequency of use of laundry equipment in the USA, and resulted that as number of the members of a dwell raises then laundry is used more often. Another research by Kavousian et al [17] revealed that households at USA using energy efficient appliances had higher minimum consumption attributed to the "rebound effect".

Fintan McLoughlin et al [18] examined the influence of household type and occupants on domestic electricity consumption patterns. The data were acquired by a smart metering survey of a representative 4200 Irish dwellings, at half hourly

intervals. Socio-economic, demographic and dwelling characteristics are considered too. A robust connection it was found between some appliances (tumble dryer, dishwasher and electric cooker) and maximum demand. Occupant characteristics inclined on the time of use (ToU) for the maximum electricity demand.

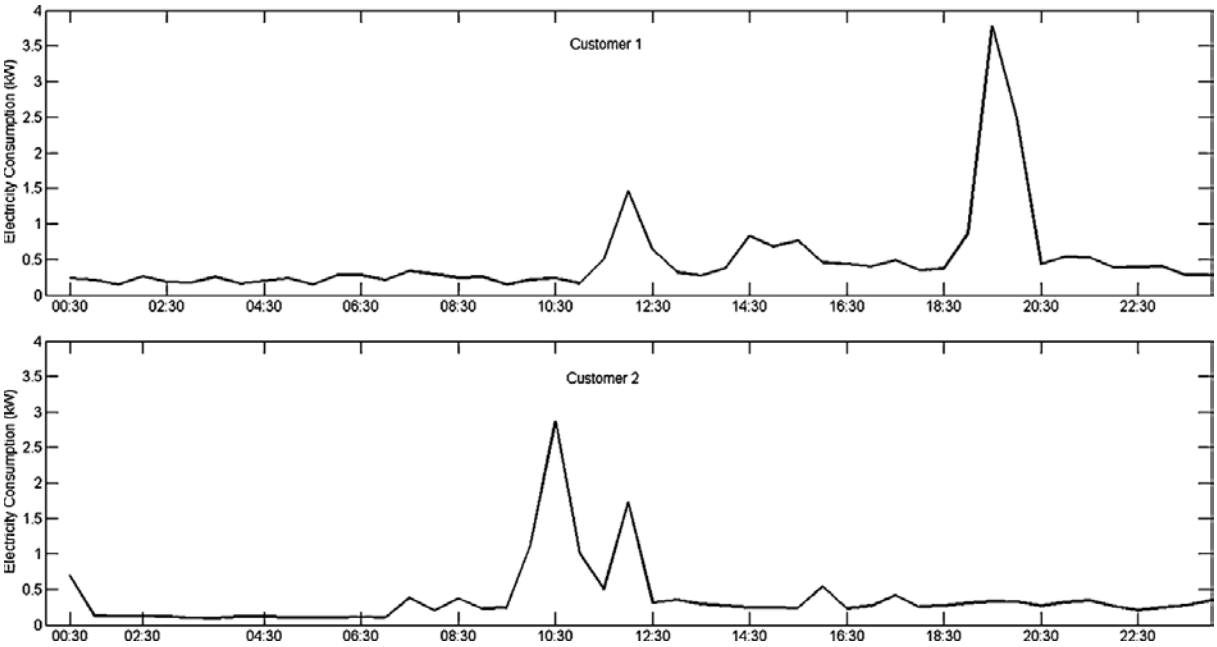


Figure 1-11 Daily electricity load profile for an individual dwelling across a 24 h period.

Figure 1-11 shows two individual customer electricity load profiles, over a 24 h period for a random day. The differences between the customers are apparent with Customer 1 having two distinct peaks, one in the late morning and another in the evening time.

The time of the day that peak loads appeared on load profiles calculated by the load factor E_{LF} eq. (1.1) which is defined as the fraction of the daily mean to daily maximum electrical demand, and is a measure of "peakynes" of a load profile. Large values indicate that electricity consumption distribution is being more evenly across the day, and low values corresponds to small intervals of large energy consumption.

$$E_{LF} = \frac{1}{m} \cdot \sum_{j=1}^{m} \frac{(1/n) \cdot \sum_{i=1}^{n} E_i}{max\{E_i, 1 \leq i \leq n\}} \tag{1.1}$$

where, *Ei* is the electrical demand in kW per time period, *n* is the total number of periods in a day, e.g. hours, and *m* is the total number of days per period.

1.5 HOUSE APPLIANCES

House appliances that used in residential buildings to meet the needs of residents are for purposes such lighting, ventilating or cooling and heating, domestic hot water (DHW), cooking, audio-visual, personal computers and others like chargers, vacuum cleaner, hair dryer etc. At figure 1-12 are depicted the energy shares of energy consumption by type of appliance from a research of the Greek Statistical authority and the Center of Renewable Energy Sources (K.A.P.E.) carried out at the period October 2011-September 2012 in residential buildings in Greece[19].

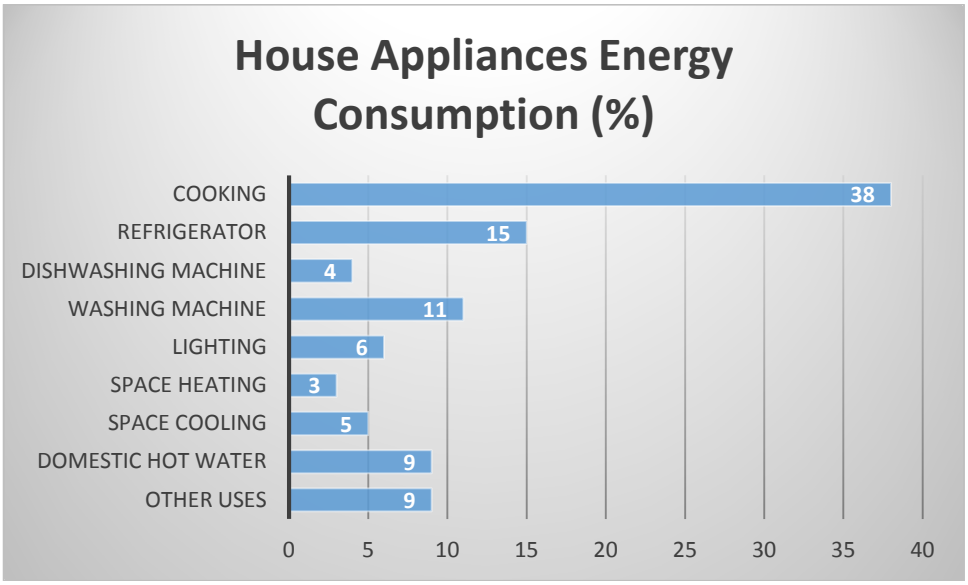


Figure 1-12 Distribution of the electric energy consumption in Greek households from the research conducted by the center of renewable energy resources (source: K.A.P.E.).

Basically house appliances are divided in three main categories; white appliances, audio visual and telecommunication appliances. White are the appliances like refrigerator, oven, and washing machines (for dish and laundry). Also, these are separated in sub-categories with criteria the importance of use and in series of more to less important are essential for life, must have, very important, nice to have and real luxury (table 1-2).

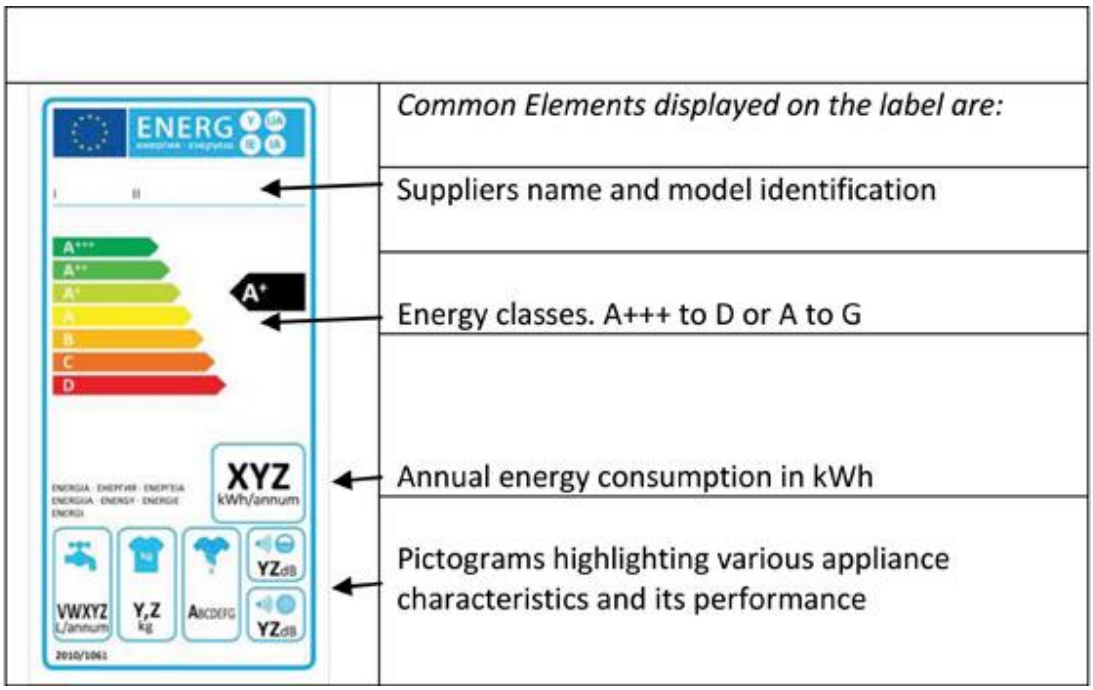
Table 1-2 Scale for the importance of appliances

	Importance	Appliances
1	Essential	Medical equipment, emergency light
2	Must have	Cooking, Refrigerator, Washing machine, light
3	Very important	Heating, Hot water
4	Nice to have	Music, TV, Radio, Internet access
5	Real luxury	Ambient light of TV set

The priorities in energy consumption should be individually adjustable. They could take place depending on the situation, for example if someone is feeling cold then heating is more important than cooking.

Many methods have been proposed for appliances profiling in terms of energy consumption. All these efforts measured the consumption while the devices where in use. Some devices appear in two conditional states with maximum power and zero power (e.g. electric kettle), but for others it is more difficult as it has various consumption levels (e.g. for PC the performance of the processor, states: active, idle, sleep mode, off mode).

The profiling of appliances is standardized and then it can be compared under a universal frame. In EU the last 15 years introduced energy labels for appliances (Directives 92/75/EEC, 2010/30/EU) and produced a trend in the sales of more efficient appliances. The consumers can easily identify, by energy efficiency labelling, the most efficient device from various models that are divided in classes from A to G. Even better classes of energy (A+, A++ and A+++) and the broadening of appliances labelled are thought to produce even greater savings.

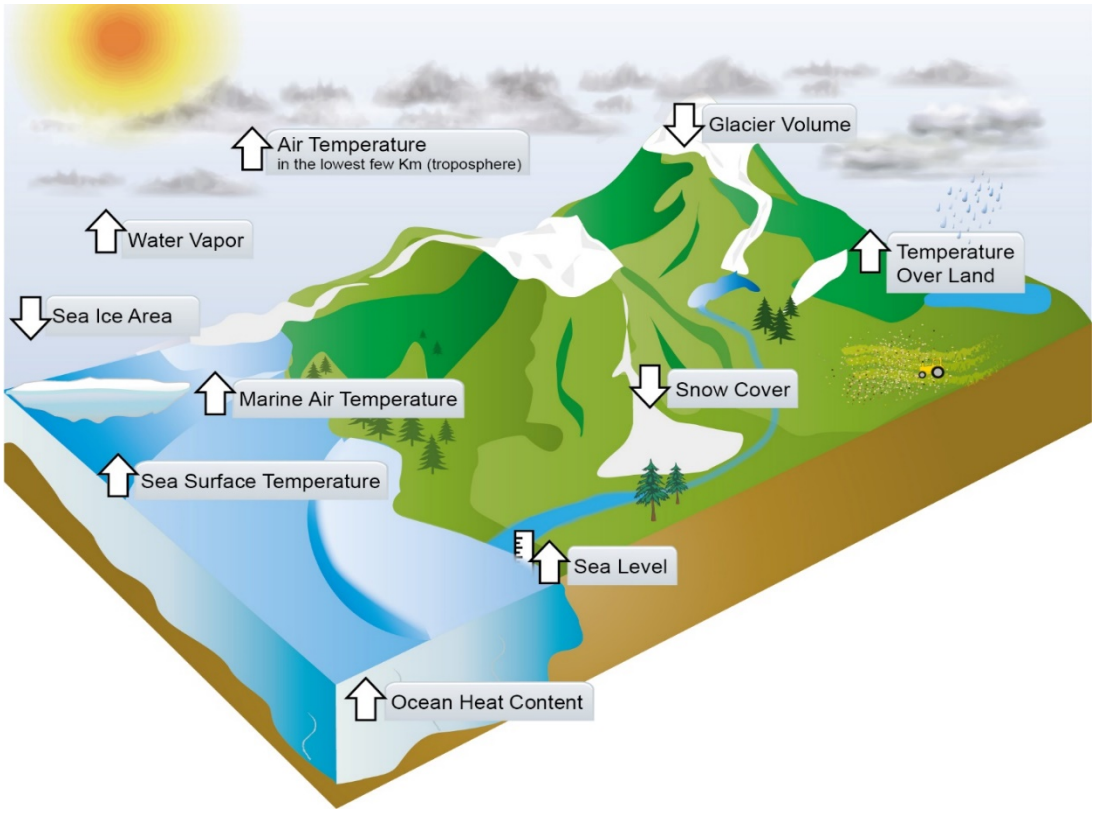


Picture 1-1 Labelling sample of house appliances energy consumption.

2 RENEWABLE ENERGY SOURCES

2.1 CLIMATE AND GREENHOUSE GASES EMISSIONS

Climate on Earth has changed throughout history and seven cycles of glacial advance and retreat appeared at the last 650.000 years. The rapid end of these periods launched 7.000 years ago with the beginning of human civilization. Since then, climate changes attributed to small variations on Earth's orbit and accordingly to the intensity of the incident solar radiation[9].

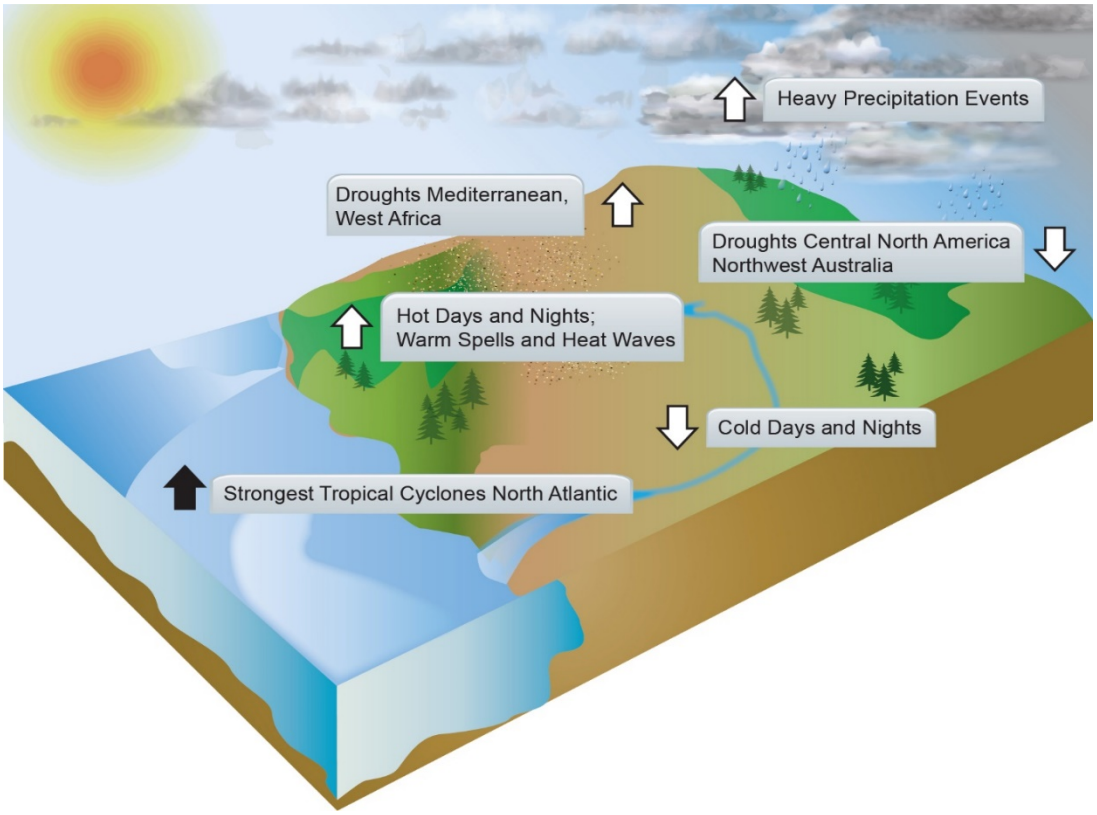


Picture 2-1 Independent analyses of many components of the climate system that would be expected to change in a warming world exhibit trends consistent with warming (arrow direction denotes the sign of the change. (source: Climate Change 2013: The Physical Science Basis, Fifth Assessment Report (WGI AR5), Cambridge University Press, page 40)[10].

It is distressing the fact that all these changes happen in very short period of time comparing to the previous. Evidence of climate change presented by researchers enclose the global temperature rise, sea level rise, warming oceans,

[9] http://climate.nasa.gov/evidence/
[10] http://www.climatechange2013.org/

shrinking ice sheets, declining Arctic sea ice, glacial retreat, extreme weather events, ocean acidification, and decreased snow power.



Picture 2-2 Trends in the frequency (or intensity) of various climate extremes (arrow direction denotes the sign of the change) since the middle of the 20th century (except for North Atlantic storms where the period covered is from the 1970s) (source: Climate Change 2013: The Physical Science Basis, Fifth Assessment Report (WGI AR5), Cambridge University Press, page 219)[11].

Renewable energy technologies emits lower greenhouse gasses than convectional for electricity production. As a comparison between natural gas that produces between 0.27-0.91kg of CO_2/kWh and coal 0.64-1.63kg of CO_2/kWh renewables emit 0.0091-0.018kg of CO_2/kWh for wind, 0.03-0.09kg of CO_2/kWh for solar, 0.045-0.09kg CO_2/kWh for geothermal, and 0.045-0.23kg of CO_2/kWh for hydroelectric energy. Biomass as a renewable source has a wide range depending on the resource and how is harvested. It can be divided in two categories of sustainable and unsustainable which emits important amounts of hazardous gases[12].

[11] http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter02_FINAL.pdf

[12] http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/public-benefits-of-renewable. html#globalwarming

2.2 RENEWABLE ENERGY RESOURCES

Fossil fuels are non-renewable, that is, they draw on finite resources that will eventually dwindle, becoming too expensive or too environmentally harmful to retrieve. Renewable energies are provided from natural resources which replenish constantly. The forms that appear are solar, wind, geothermal, ocean, hydropower, and biomass. Next, a short description of these resources/fuels is given.

Solar energy can be used directly or indirectly either for heating or electrifying houses and other buildings, for electricity generation, water heating, solar cooling, and a range of commercial and industrial uses.

Wind is the energy produced by air mass flows. It is one of the most common forms and has many applications in humanity for ship movement or windmills, and at the last decades for electricity production with wind turbines.

Hydroelectric is the power that can be generated from captured river flows in plants that use water turbines.

Biomass is the organic matter that makes up the plants (trees, sugar cane, flowers and etc.) and can be used in electricity production or fuels in transportation and even in chemicals. The energy from these procedures is called bioenergy.

Geothermal energy exploits the Earth's internal heat for a range of uses like electric energy production, natural heating and cooling of the buildings.

Ocean energy comes from the ocean's waves driven by the winds and tides. Tides are created by the gravitational pull of the moon and the sun upon the Earth. Also, the temperature difference of the ocean's surface, heated by the sun, and the depth is another energy resource. All of these types of ocean energy can be used for electricity production.

Different energy resources can be implemented for different energy purposes. The three basic categories for the use of RES are:

- Power generation (PV plants, wind farms, hydroelectric plants and others).
- Heating and cooling (solar water heating, solar cooling, geothermal heat pumps).
- Transportation (biofuels).

2.3 TECHNOLOGIES RELATED TO RENEWABLE ENERGY

This section is an overview between different types of renewable energy technologies, wind, solar, biomass, hydro, and geothermal. The environmental benefits of renewable energy is difficult to take into account in terms of cost

saving through less pollution or less damage to the environment. To do that it would be preferred a life cycle cost approach, as the initial cost may be high but instead the operation and maintenance costs are very low.

2.3.1 Wind turbines

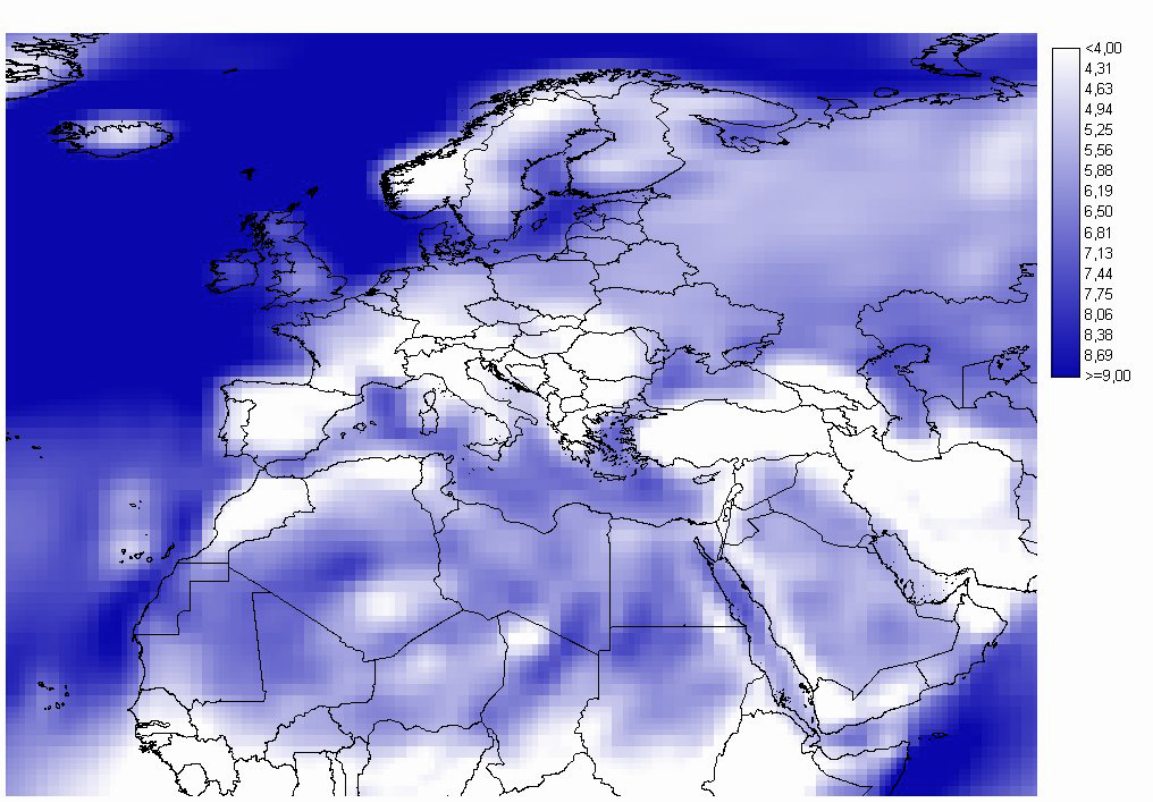


Figure 2-1 Annual average wind speed at 80 m above ground level in m/s. (source: German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment, Concentrating Solar Power for the Mediterranean Region, 16 April 2005).

A wind turbine (WT) exploits the energy from moving air masses to convert it into electric energy. Wind power acts on the rotor blades into torque and subsequently the rotational energy is used within a generator for electricity production. Generator's size varies widely; the length of the blades is crucial for the amount of electricity that can be produced. Small turbines commonly used in building sector their capacities range from a few hundreds to thousands of Watts. In contrast, larger WT have power that can reach millions of Watts; and if they grouped together to create power plants that called wind farms that provide electricity to the grid.

Some types of wind generators are:





- Horizontal-axis (HAWT), are the most common type in the market and usually they have three blades. Mostly used in wind farms.
- Vertical-axis (VAWT), they are attached at the top or bottom of a vertical rotor. Rarely found at the market because of its low performance comparing with the horizontal. The most common types is Darrieus (left picture) and Savonius (right picture).
- Bladeless windmill: It is a structure without any moving or mechanical parts, but with spraying positively charged particles. (Delft University of Technology, Germany).
- Bumblebee Design: A revolutionary design and a clever example of bio-mimicry. Presented by Green Wavelength, a company in California, it is 19ft tall and constructed by aluminum and carbon fiber.
- Heliwind: Replaces blades and tower of a conventional wind turbine with a lighter than air helical balloon and lowers the generator to the ground. Created by the Hawaii Consulting Group.

Classes of wind turbines:

- Class I: Designed to cope with the tough operating conditions experienced at sites with average speeds above 8.5m/s.
- Class II: This is the most common class of wind turbines that is available and are used for sites with average wind speeds up to 8.5m/s.
- Class III: Typically they have large rotors to capture as much energy as possible. They work for wind speeds averages up to 7.5m/s.

Wind turbines might also be flown in high speed winds at altitude. Altaeros Energies produced an airborne wind turbine, which has an inflatable helium-filled shell that lifts it at high altitudes over the ground where wind speeds are stronger. Airborne turbines are held steady by strong tethers, which also send electricity generated by the wind turbine to the ground.

Picture 2-3 Airborne wind turbine by Altaeros Energies company. A viable clean energy option for remote villages and military sites.

Wind energy systems are classified in two basic categories; grid connected or off-grid. In first case produce electricity that can contribute to the utility grid and on the second they usually combined with other renewable generators like PV's and/or conventional diesel generator as stand-alone (autonomous) systems. Regularly, a backup system in the second category is connected to the system for the times that generators can't meet the loads demand.

Table 2-1 Wind energy systems, pos and cons

	Pos	Cons
1	Simple technology with lifetime of over 20 years	Requires a suitable site
2	High automation with low maintenance costs	Storage/backup is obligatory in the case of autonomous systems
3	Fuel free	High initial costs that prevents development
4	Low Environmental impact	Potential market needs to be large because of the implementation of expertise people and equipment

In table 2-1 are presented the strengths and weaknesses of the use of wind turbines for electricity production.

Modern WT are produced in a variety of electrical capacities ranging between less than 100W and reaching 3MW. And those which are integrated on

buildings not surpass the nominal power output of 3kW, or if sited on the ground of buildings might reach 50kW. Overall, roof-top generation in urban environment is out of favor because of the limited rotor diameters that can be applied and as a result low energy production. Deploying the fact that wind power generation and loads consumption differentiates timely, it would be useful if a storage medium was used or even the produced energy could be sold to the grid, via a reversible meter (net-metering). Important factor for the proposal of WT in urban cases should be the noise pollution as it is proportional to 5^{th} power of the tip speed and at high speeds might be annoying audible by neighbors.

Picture 2-4 A whisper type wind turbine on the roof of Renewable Energy Systems & Sources Laboratory roof, Technological Educational Institute of Western Greece, Patra.

Picture 2-5 A wind farm on Panachaiko mountain at the gulf of Korinthos, near Patra, Western Greece.

2.3.2 Solar technologies for power generation

The energy that comes from solar radiation can be converted into heat and electricity. In the first case, the conversion to electricity is provided by PV modules and heat by solar panels. A combined energy can be generated by solar thermal panels where the energy of the solar radiation directly converted to electricity and the heat produced on the module transferred to a fluid at the back and provided for use to the consumer (e.g. domestic hot water).

PV modules consisted of cells connected in series and parallel in order to produce power with the appropriate characteristics for current and voltage. Larger surfaces produce greater amounts of power and when modules connected in groups create PV arrays. Therefore, the total amount of electricity is defined by the number of used panels. The photovoltaic systems can be divided into fixed and solar tracking of two or three axis. Solar trackers are used to achieve the best possible angle of incidence for sun rays, and exploit the biggest proportion of solar energy that can be provided.

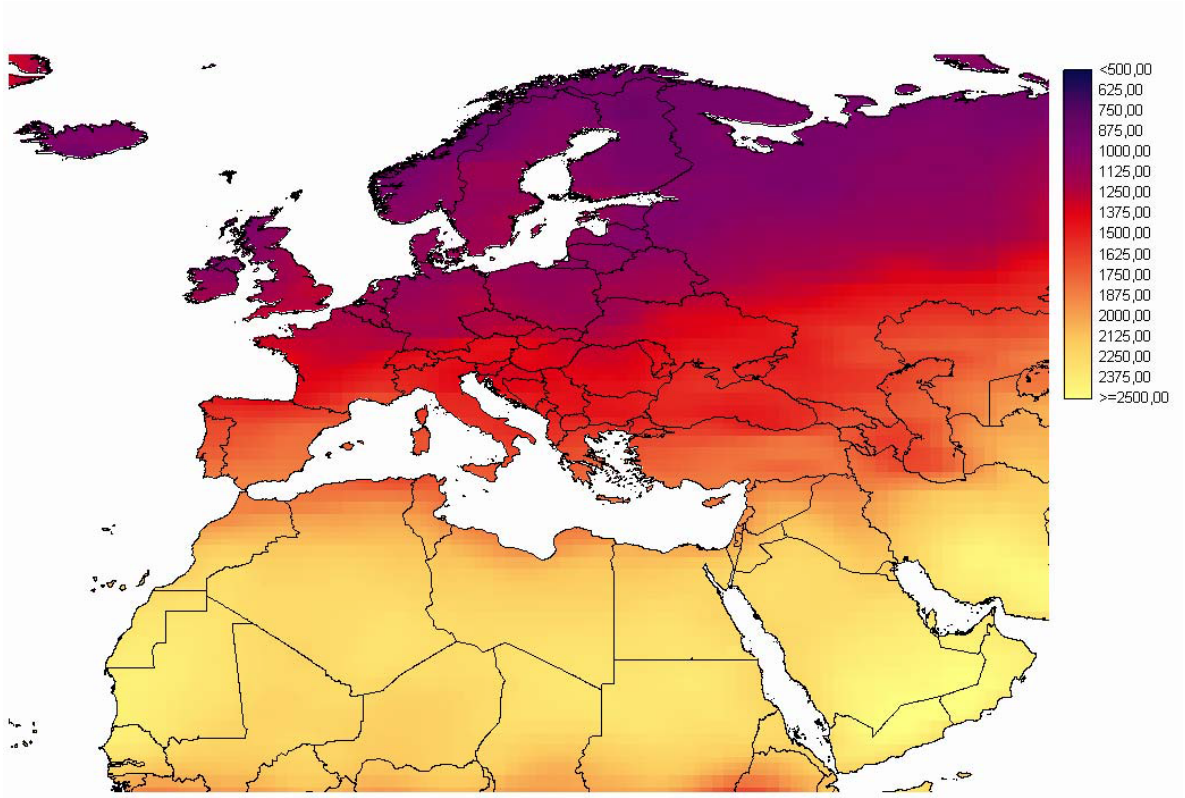


Figure 2-2 Annual Global Irradiation on Surfaces Tilted South with Latitude Angle in kWh/m²/year. (source: German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment, Concentrating Solar Power for the Mediterranean Region, 16 April 2005).

The amount of energy produced by PV's depends on the sunshine density. They are capable to produce even on cloudy days at a reduced rate. Because of the dependence on the sunshine duration and the angle of incident of sun rays their performance is seasonally variable with the peak period being in summertime. Except of the seasonal there is also a variation on a diurnal basis with peak hour being at solar noon.

Some factors that affect the performance of PV modules are the partial shading of a module that it can seriously degrade the PV performance; aging effects enclosing degradation by weathering, initial photon degradation, module package degradation, temperature increases module power output when rising upon 25-30 ºC, dirt and dust, mismatch and wiring loses; and the PV inclination which can reduce the performance significantly (high temperature on integrated modules, or high proportion of reflected radiation).

In PV technology a semi-conductor transforms under chemically the solar energy into DC current. The base material that constituted of is silicon at approximately 90%.

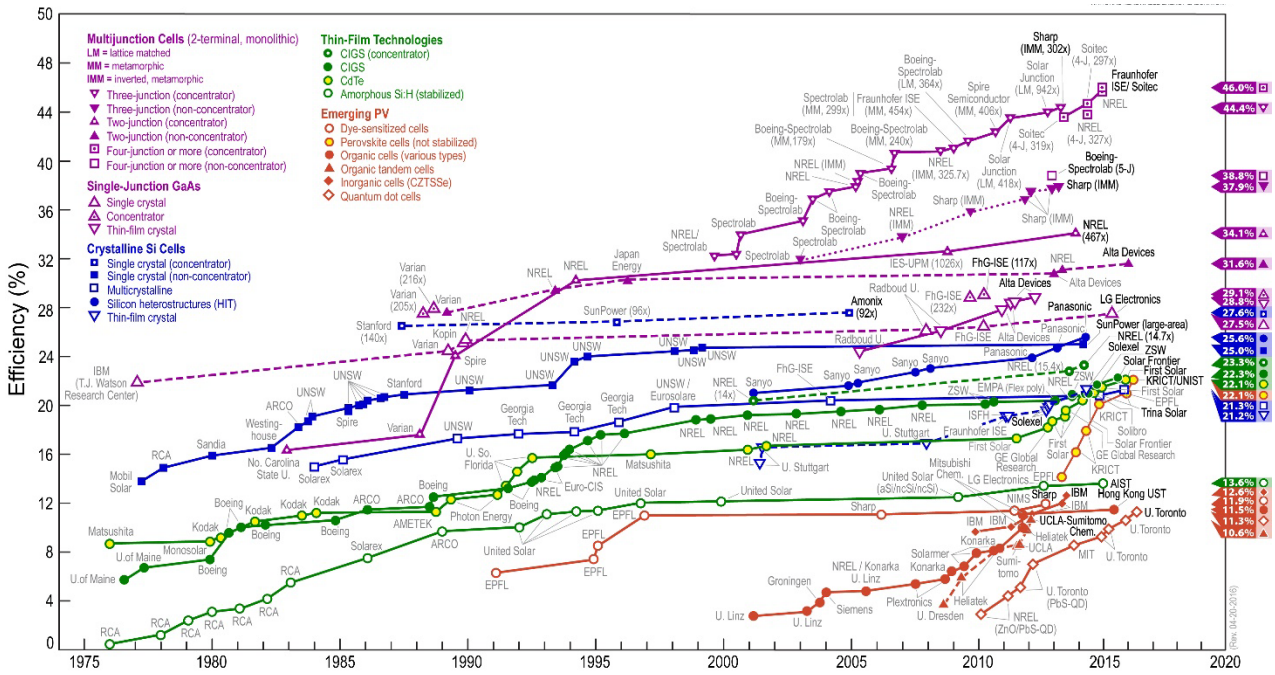


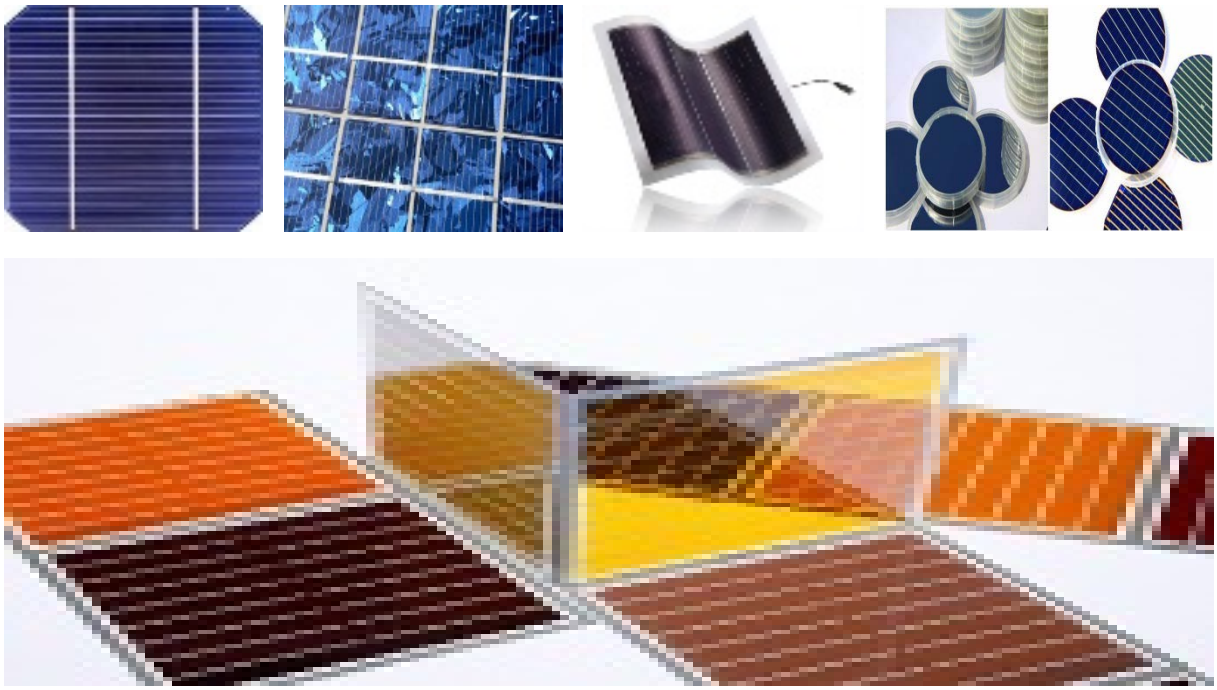
Figure 2-3 Growth of PV cell efficiencies over the years for all the different technologies. (source: U.S. National REnewable Laboratory, NREL[13])

Basic types of photovoltaic cells:

- Single-crystalline silicon (sc-Si) modules, use the purest form of silicon and comprise highly ordered blue-black polygons. Is the most expensive and efficient type as it reaches the portion of 16-20%. Life expectancy is around 25-30 years.
- Multi-crystalline silicon (mc-Si) modules, can produce less energy per area provided than monocrystalline and with lower efficiency typically close to 12-16%. Life expectancy is around 20-25 years.
- Thin-film modules, consisted of an ultra-thin layer of photosensitive material deposit on a low cost backing material, like glass or plastic. A type of such kind is amorphous silicon (a-Si). Also, thin hybrid silicon which consists of amorphous and microcrystalline cells. Other technologies use as semiconductor material cadmium telluride (CdTe) and copper-indium-gallium-diselenide (CIGS) with performances around 8-9% and 10-13% respectively. They are rigid or flexible and in various colors. Production cost is low and efficiency ranges at 4-8%; nowadays can reach 15%. Life expectancy at 15-20 years.
- Multi-junction cells are composed of several cells overlying in a stack. It creates double (tandem), triple, or quadruple junctions and enables a wider spectrum of light to be trapped.

[13] http://www.nrel.gov/ncpv/

- Dye Sensitized Solar Cells (DSSC), is a photoactive material which catches photons of the light to excite and eject electrons (e^-) that conducted away by nano-crystalline titanium dioxide. At last, an electrolyte closes the circuit of this process and e^- are returned back. Their efficiency is in the region of 9-13%.



Picture 2-6 Types of PV cells. Up and left to right: single-crystalline, multi-crystalline, thin-film, multi-junction and down dye sensitized solar cells DSSC or DSC.

Other technologies which are under development are organic cells that use organic polymers as semiconductor and appear with low efficiency, quantum dots are very small nanocrystals of semiconductor with lower cost production and higher efficiency than silicon and last dye-sensitized cells that use dye-coated titanium dioxide nanoparticles.

Table 2-2 Strengths and weaknesses of PV energy systems

	Pos	Cons
1	High reliability and long lifetimes	Dependence on local weather and sunshine level
2	Low maintenance requirements	Storage back-up usually required. Can't produce during night
3	No require for fuels	High initial capital costs
4	Allows a complete range of sizes as application dictates	Specific training and infrastructure needs
5	Low environmental impact	Energy intensity of silicon production for PV solar cells
6	User is less affected by rising prices for other energy sources	Some PV modules use toxic materials

The most hopeful applications of PVs are in large scale power generation and mounted in buildings. New approach in integration technologies is cladding of basically commercial buildings in PV materials. A major disadvantage of the particular technology is the need for much more land for installation than e.g. of a fossil fuel plant, for big amounts of energy.

Different types of installations can be found for PV systems depending on the place, the available space and also the capital investment. The most popular are the ground mounted or roof mounted or integrated steady. Sun tracking systems, with one or two axes, can be found where the need of exploiting higher portions of solar energy is intended. Conventional PV panels can also be fixed to the external walls of buildings with bracketing systems. Furthermore, they can replace architectural elements made of glass, double or triple glazing units with PV cells built in, like windows, canopies, balcony systems and etc.

Picture 2-7 A sun-tracking PV system vs a fixed inclination one. 4 PV panels pc-Si of 122 Wp each are mounted on both frames, at Renewable Energy Sources Laboratory at technological educational institute of Western Greece, Patra.

Picture 2-8 A PV power plant of 9.99MW_{peak}, at Farsala Greece. Occupies an area of 34,900m^2 and consisted of 21,274 PV polycrystalline silicon modules.

Picture 2-9 Applications of building integrated PVs at rooftops, building facade, windows, sunshades and the gorgeous solar arc at Sanyo's semiconductor factory in Gifu, Japan (bottom and right).

2.3.3 Biomass technologies

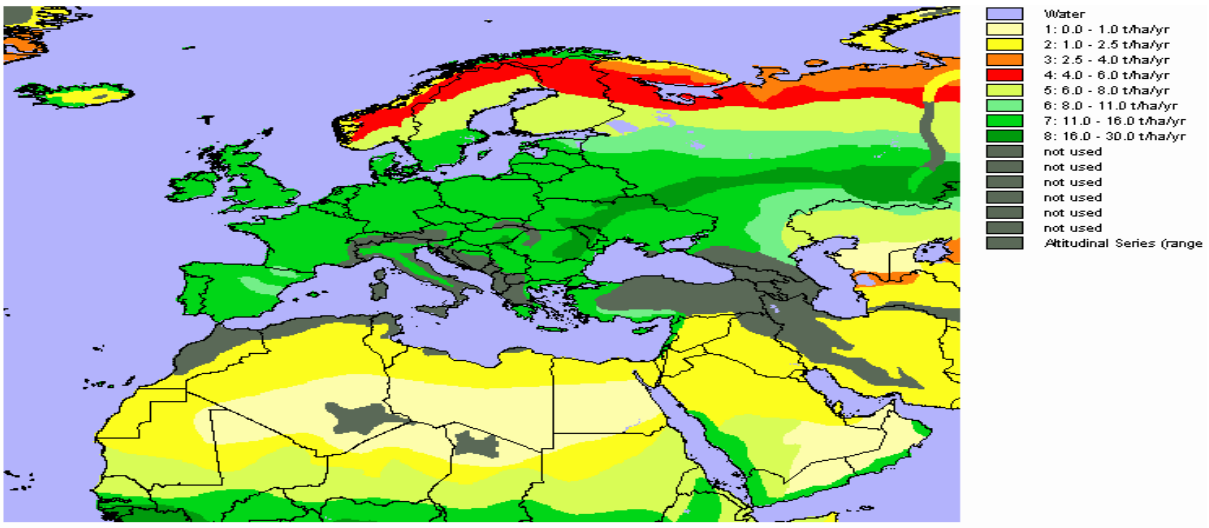


Figure 2-4 Map of biomass productivity. (source: German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment, Concentrating Solar Power for the Mediterranean Region, 16 April 2005).

Bioenergy is the energy derived by materials of plants or animals origin. Sources of bioenergy are wood, residues of wood, agricultural crops and residues, animal fats, animal and human wastes; all of these yield useful fuels directly or after the appropriate conversions. Technologies are used for direct combustion or using liquid or gaseous byproduct. The process can be physical (drying, densification and others), thermal (carbonization) or chemical (biogas-anaerobic digestion).

Table 2-3 Primary and secondary technologies for the production of heat, electricity, and transportation fuels.

Primary energy conversion technologies			
Combustion	**Gasification**	**Pyrolisys**	**Biochemical**
Heating	Fuel gas	Fuel gas	Methane
Steam Production			Liquid fuels
⇩			
Secondary energy conversion technologies			
Steam turbines	Internal combustion engines	Internal combustion engines	
Stirling engines	Micro-turbines	Gas turbines	
	Gas turbines		
	Fuel cells		
⇩			
Low range applications			
Heat	Electricity	Transportation fuels	

The basis for all these applications is organic matter; mostly from plants and trees. Biomass can either produced by planted crops or collected as a by-product and residue from agricultural, forestry, industry and household waste. It can be used for a variety of needs like heating, transportation and power generation.

In transportation most popular biofuels is ethanol and biodiesel. Both are blended with petroleum fuels (diesel or gasoline); they can also burned on their own. Biofuels are cleaner forms and less pollution gases are emitted. Ethanol is an alcohol and mainly produced from grains like corn, sorghum, and barley. Other sources for ethanol might be sugar cane, rice, sugar beets, and potato skins. Biodiesel produced from vegetable oils and animal fats. Sources that can produce biodiesel are soybean, canola oil, corn oil, rapeseed oil, sunflower oil and palm oil. Animals by their fats can provide biodiesel and even grease from restaurants can be transformed and used as fuel. Biodiesel when blended with petroleum is written with the form for example B2 where 2 represents the fraction of biodiesel. Pure biodiesel is B100.

Table 2-4 Bioenergy weakness and strengths

	Pros	**Cons**
1	Available technologies in wide range of power	Encumbrance of heavy computation and possible single-point failures.
2	Fuel production and conversion technology indigenous in developing countries	Large areas of land required
3	Can produce more jobs than other renewable energy systems of similar size	Production can have high fertilizer and water requirements
4	It appears in different forms (gaseous, liquid and solid) as a fuel	Possible requirement of complex management for constant supply of resource
5	Low environmental impact compared with conventional energy sources	Resource production varies depending on the local climatic/weather effects

Table 2-5 Several technologies of biomass for power generation[14].

Technology	Description	Types
Combustion	Direct combustion of biomass for power generation is a mature, commercially available technology.	Stoker boilers burn fuel on a grate, producing hot flue gases that are then used to produce steam. The ash from the combusted fuel is removed continuously by the fixed or moving grate. Fluidised bed boilers suspend fuels on upward blowing jets of air during the combustion process. They are categorized as either atmospheric or pressurized units.
Anaerobic Digestion	Anaerobic digestion (AD) is a naturally occurring process converts biomass feed stocks with a relatively high moisture content into a biogas, and can be harnessed to provide effective treatment of organic materials (energy crops, residues, industrial, agricultural and municipal wastes).	Appropriate digester: 1) Covered lagoon digester/ Up flow anaerobic sludge blanket/Fixed Film 2) Complete mix digester 3) Plug flow digester
Gasification	Gasifier technologies offer the possibility of converting biomass into a producer gas, which can be burned in simple or combined-cycle gas turbines at higher efficiencies than the combustion of biomass to drive a steam turbine.	1) Fixed bed gasifiers 2) Fluidized (circulating or bubbling) bed gasifiers 3) Entrained flow gasifiers
Pyrolisis	Pyrolysis is a subset of the gasification system and uses the same process as gasification, but the process is limited to between 300°C and 600°C.	

[14] https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf

Picture 2-10 A sewage treatment plant at Chiclana at Frontera, Spain is the world's first plant that will be used to convert sewage into renewable algae biofuel that can be used as fuel for vehicles.

2.3.4 Hydro turbines

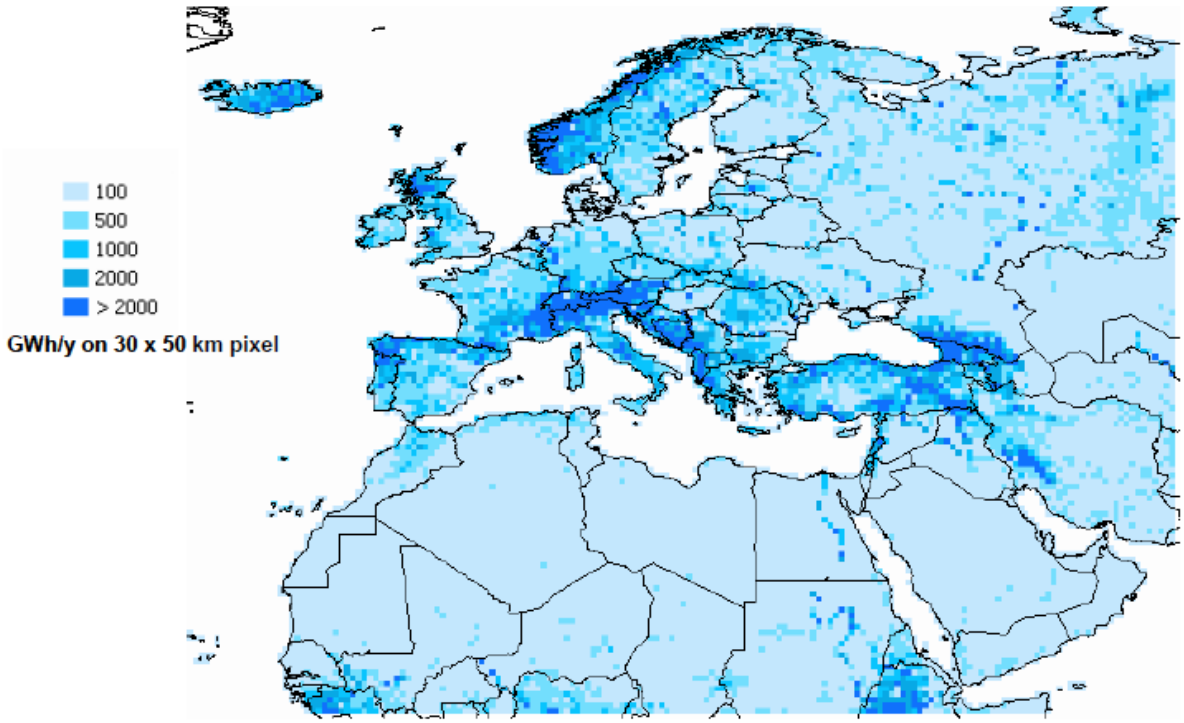
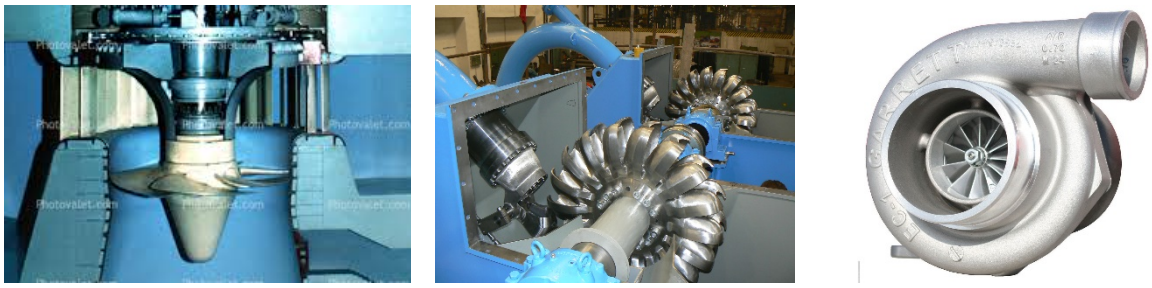


Figure 2-5 Gross Hydropower Potentials in EU-MENA. (source: German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment, Concentrating Solar Power for the Mediterranean Region, 16 April 2005).

Knowledge of water cycle is important for understanding hydropower. This procedure enclosed in three steps:

- Solar energy heats water on surface and causes evaporation.
- Water vapor then condensed into clouds and falls as precipitation (rain, snow and etc.)
- Next water molds river flows that pour in seas and oceans.

The available amount of energy in moving water is determined by the volume of flow and the elevation from one point to another. Water flows through a pipe and then pushes against and turns blades in a turbine to spin the generator and produce electricity. In a run-of-the–river system the force of the current applies the needed pressure, whereas in a storage system, water is accumulated in reservoirs created by dams. Many types of hydro-turbines are available to transform mechanical energy from river flows to electricity, such as Pelton, Francis, Kaplan depending on the characteristics of the river (flow, manometric head[15] and etc.) and installation capacity.



Picture 2-11 Different types of hydro turbines (left to right: Kaplan, Pelton, Francis).

Hydropower systems vary between tens of Watts to thousands of MW. A classification of the different sizes of hydropower is shown in table 2-6:

Table 2-6 Classification of hydro-power size depending on the size.

	Type	Output
1	Large hydro	More than 100MW, usually for large electricity grids
2	Medium hydro	Capacity from 20MW to 100MW, for feeding electricity grid
3	Small hydro	Their capacity varies from 1MW to 20MW, for feeding electricity grid
4	Mini hydro	Capacity is between 100kW to 1MW, for feeding the grid and rarely for stand-alone systems
5	Micro hydro	5kW to 100kW, mostly in remote areas for rural or small community electrification
6	Pico hydro	50W to 5kW, for remote areas and individual households. Storage system, such as batteries is used

A dam may obstruct fish migration. It can also change natural water temperatures, water chemistry and river flow characteristics. All these changes

[15] Manometric head is the difference in elevation between upstream lever of reservoir and downstream level (turbine).

sometimes have negative impacts to the ecology, physical characteristics of the river, on native plants and animals around the river. Because of the large area that they cover there is sometimes an effect on agricultural land, and might also cause the relocation of people. The use of a dam has a great impact over a larger area than the area covered by a reservoir.

Table 2-7 Small hydropower plants strengths and weaknesses.

	Pros	**Cons**
1	Simple technology with lifetimes of over 30 years without investment	Site-specific technology mostly close to the power needed
2	Overall costs may undercut other alternative solutions	For small streams the maximum power is limited without prospects for power expansion
3	Automatic operation and low maintenance costs	Aridity and changes in local water flows and land may affect negatively power output
4	No fuel required	Low power generation on dry seasons
5	Compared to conventional sources low environmental impact	Very high initial costs for the investment
6	Predictable and constant availability of power rate at all times (depends on water source availability)	Engineering skills required which may be unavailable or expensive to obtain locally

With the right circumstances hydropower can be one of the most reliable and cost effective renewable energy sources. They characterized by reliability and flexibility in operation, including fast start-up and shut down for rapid demand changes; the only limit is water sources.

Picture 2-12 Hydroelectric dams of Pournari I and II, at Arta Greece.

2.3.5 Geothermal technologies

Is the thermal energy that is located under the ground and generally determines the temperature of the matter. It is cost effective, reliable, sustainable and environmentally friendly, but it appears mostly near tectonic plates boundaries. They are deep underground and mostly undetectable from the surface. Greenhouse gases released by geothermal boreholes are much lower per energy unit than those emitted by fossil fuels. Hydrothermal resources come on the surface in three ways by volcanoes and fumaroles, hot springs, and geysers.

Some technologies for hydrothermal exploitation use the Earth's temperature near surface, while others require drilling into the earth. The types of use of this kind of energy are:

- Direct use and district heating systems use hot water near surface (springs or reservoirs).
- Electricity production by geothermal power plants require high temperatures of water or steam (150ºC to 370ºC). Generally they placed near geothermal reservoirs that might be up to near three kilometers underground.
- Geothermal heat pumps that use the stable temperature of the ground or water near the surface.

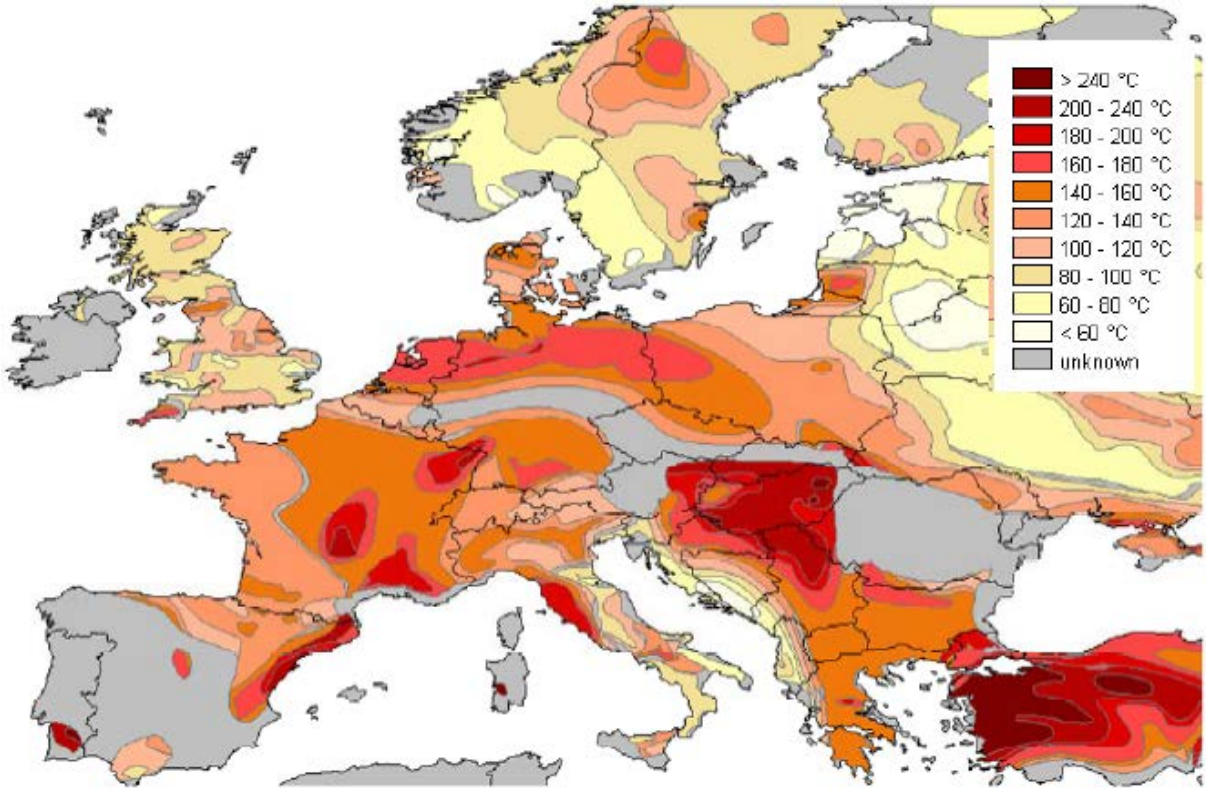


Figure 2-6 Temperature at 5000 m Depth for Hot Dry Rock Geothermal Power Technology. (source: German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment, Concentrating Solar Power for the Mediterranean Region, 16 April 2005).

At building sector geothermal energy is used through district heating systems. Geothermal heat pumps for heating and cooling exploit the steady temperature of the underground (10^{o}C to 16^{o}C) at a distance close to 3m from the surface. Obviously, soil temperatures are warmer during winter and colder during summer from the ambient temperature and are used for heating and cooling purposes for the buildings by the help of a pump piped into the building. Heat pumps transfer heat from the ground inside the buildings at winter and reversely at the summer.

In industrial use of geothermal energy it is required high temperature of hydrothermal resources (150^{o}C to 370^{o}C) that come from either dry steam wells or hot water wells. To use these resources it is necessary to drill the ground and pipe hot steam or water to the surface and operate a turbine that produce electricity. Industrial applications include food dehydration, gold mining, milk pasteurizing and etc. The plants of this type are categorized in the following types:

- Dry steam plants, where a piping system transfers the heated mean from underground directly to the generator turbines.
- Flash steam plants, represents the majority of geothermal power plants. It takes high-pressure hot water from deep inside the ground and convert it into steam to drive steam generators. From this procedure the steam is condensed to water and injected back into the ground.
- Binary cycle power plants, transfer the heat of geothermal hot water to another liquid which in turn evaporated and used to drive a generator turbine.

Technologies that can be found used for heating/cooling purposes in buildings are *borehole heat exchangers*, individually or an array close or under the building at a depth of 50-150m, *energy piles*, pipes into the buildings foundation piles necessary for structural purposes in depths between 10-30m while length and quantity is determined by static considerations, *ground absorbers*, found under or beside the foundation slab as horizontal pipe loops. And the last method is for direct use of ground water (thermally exploited), where supply well pumps are used for the circulation of water through heat exchanger and injected back after.

2.4 PENETRATION OF RENEWABLE SOURCES

Global energy intensity, primary energy consumption per unit of economic output, appeared with a decrease over the period 1990-2013 close to an average annual rate of 1.25% against the rise of renewable energy. Although, energy use rose in 2014 after four decades, global carbon emissions related to energy

consumption stabilized due to penetration of renewables and improvements on energy efficiency.

Most recent data, in 2013, revealed a remarkable attribution of renewables that reached 19.1% of global final energy consumption. Biomass accounted 9% of the total and basically used for cooking and heating purposes in remote and rural areas while modern renewables shared 10.1% over 2012 (figure 2-8).

Renewables contribution on power sector approached the proportion of 22.8% of the global electricity supplied (figure 2-9), while by the end of 2014 incorporated by 27.7% on the total power generating capacity worldwide. Hydropower achieved the highest score reaching 16.6% of the total energy provided. It must be mentioned that grew rate of the renewable penetration on power sector was 5.9% annually for the years 2007-2012. At the same time length global consumption of electricity amplified by an annual average rate of 2.7%.

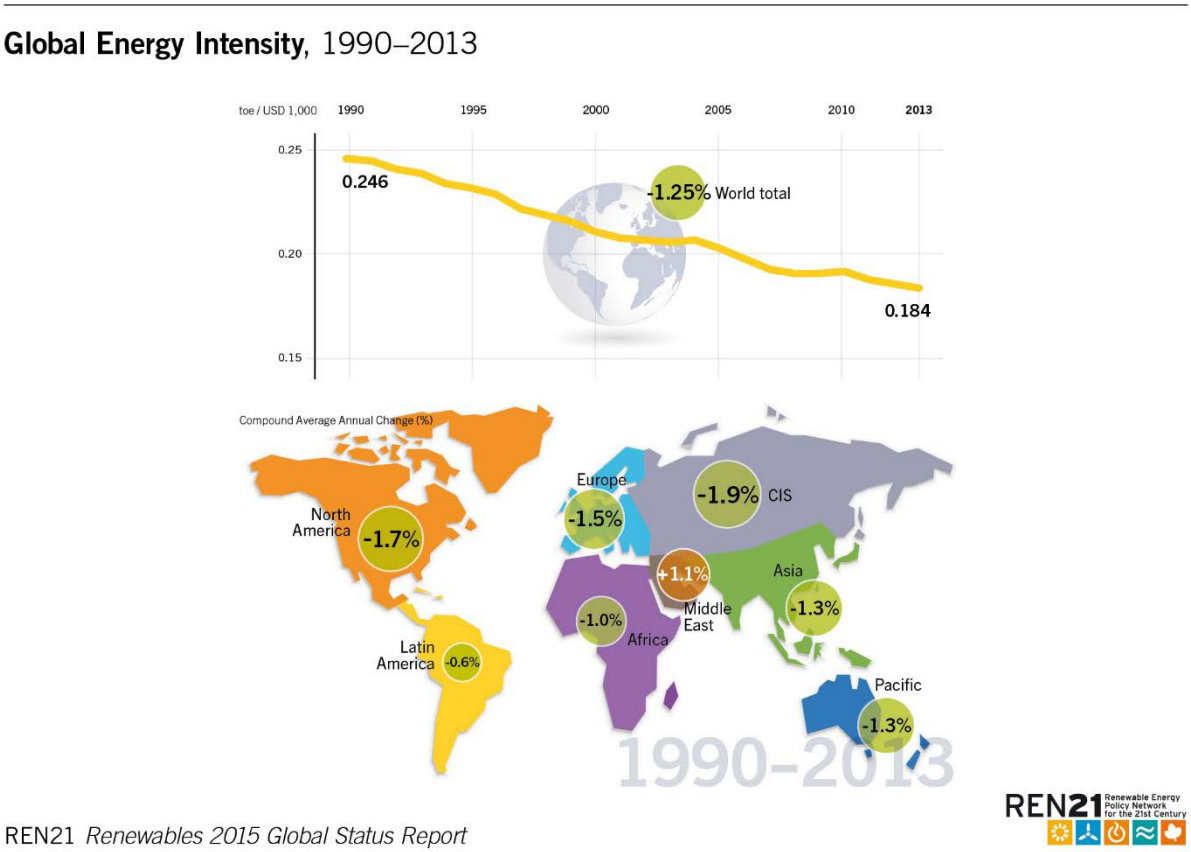


Figure 2-7 Decrease of global energy intensity with an average annual rate of 1.25% for the period 1990-2013, and per continent (source: REN21, Renewable Energy Policies for the 21st Century, "Renewable 2015 Global Status Report").

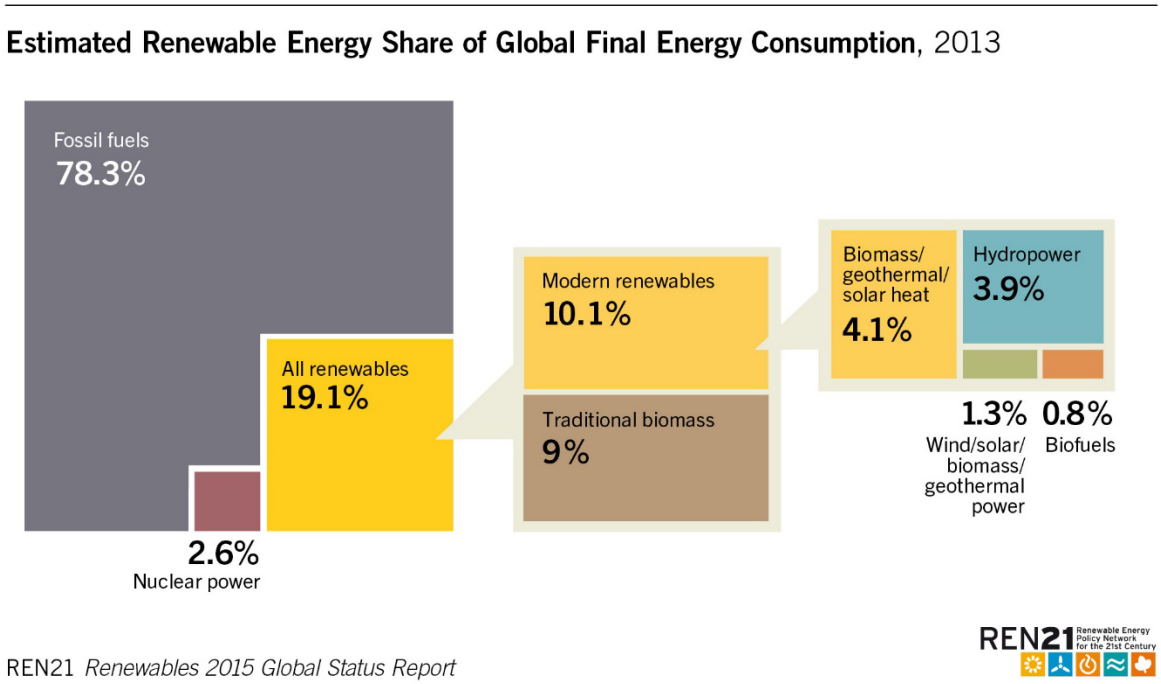


Figure 2-8 Share of renewable energy on the estimated energy consumption of global final energy consumption (source: REN21, Renewable Energy Policies for the 21st Century, "Renewable 2015 Global Status Report")

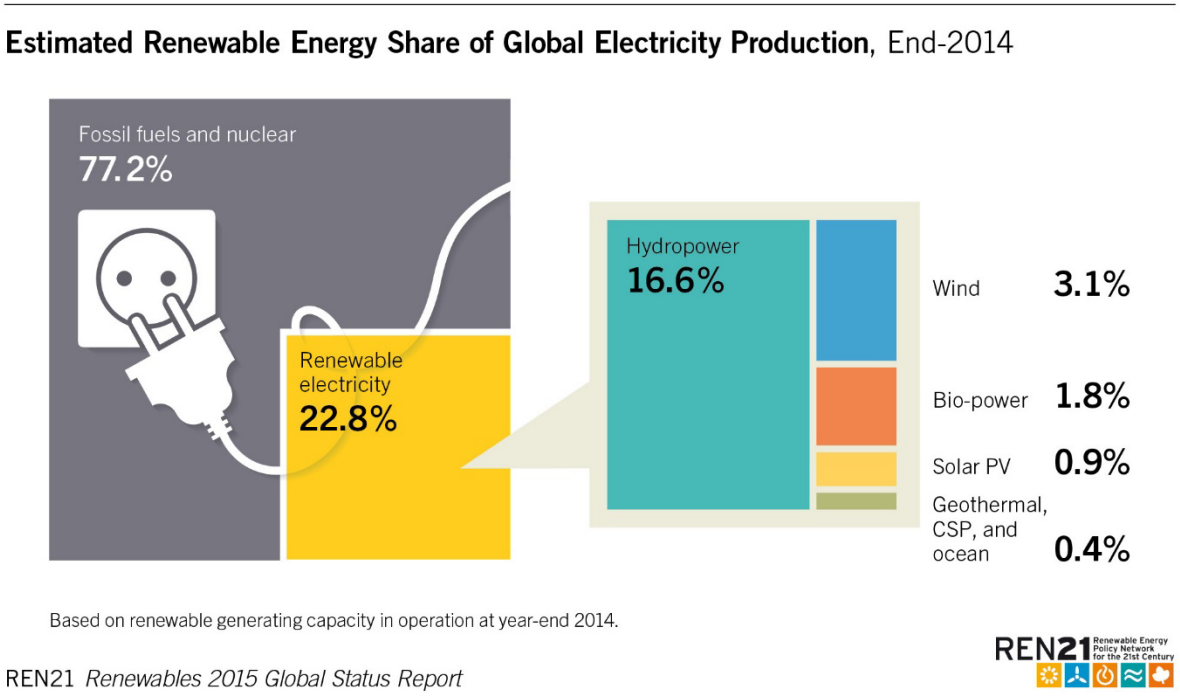


Figure 2-9 Global estimated electricity produced by renewables sources by the end of 2014 (source: REN21, Renewable Energy Policies for the 21st Century, "Renewable 2015 Global Status Report").

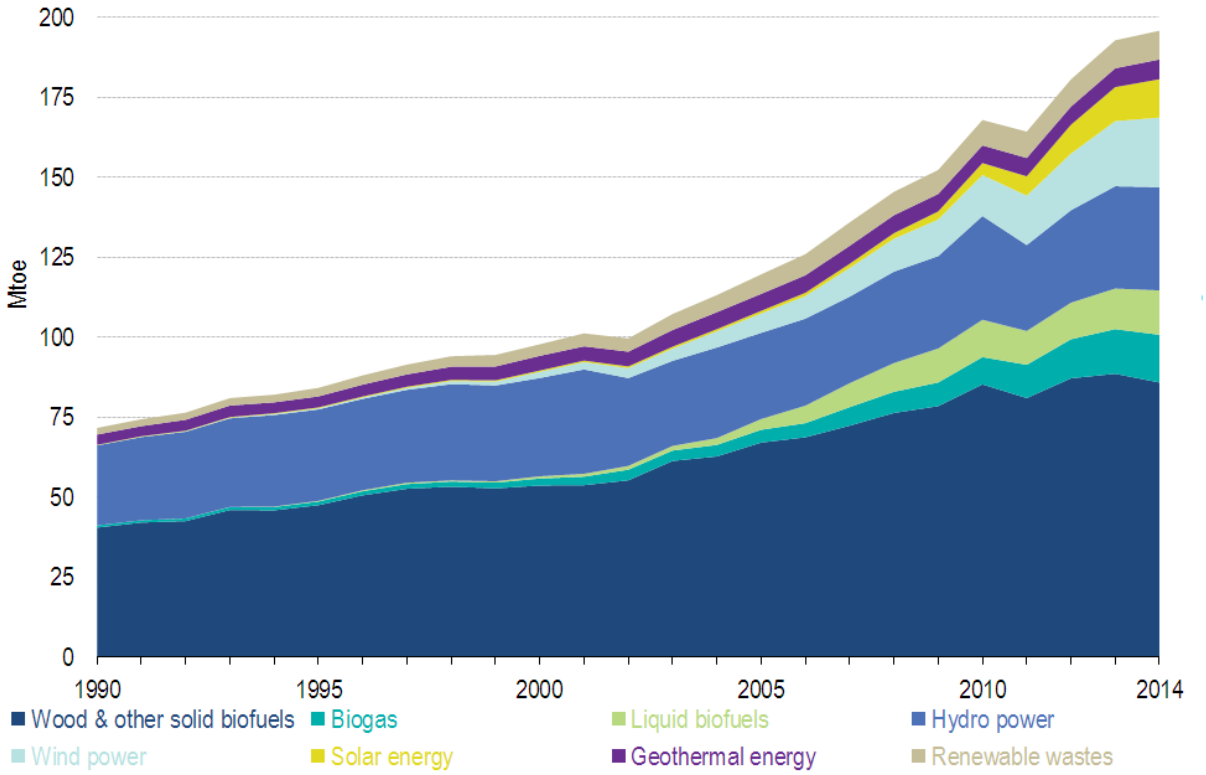


Figure 2-10 Primary production of energy from renewable sources, EU-28, 1990-2014 (source: Eurostat)

In Europe primary production of energy from renewable sources has a steep growth between 1990 and 2014 by 174% (figure 2-10). During all this period it were recorded two decreases in 2002 (-1.6%) and in 2011 (-2.2%) and an average annual growth rate of 4.3%. In both decreases the main cause was hydropower variation. In 2014 the production by renewables increased by 1.6%, in comparison with 2013 and at last 5 years (till 2014) by 29%.

Also, in gross electricity production the share of RES was increased over the period 1990-2014 by 191% with the highest increase found to be from solar power by 14.1% and the lowest from hydro power by 0.9% (figure 2-11). Hydropower plants constitute the leading part of electricity production and in 2014 their share was about 42% of the total electricity produced by renewables. Wind power penetration was increased almost three times from 2005 till 2014 and for over a decade is holds the second place. In third place in 2014 it is found solar power, with a share of 11%. Solid biomass counted the 10% the same year being the fourth contributor of RES and bioliquids and biogas was appeared with a not inconsiderable number of 7% of the overall renewable electricity production in 2013.

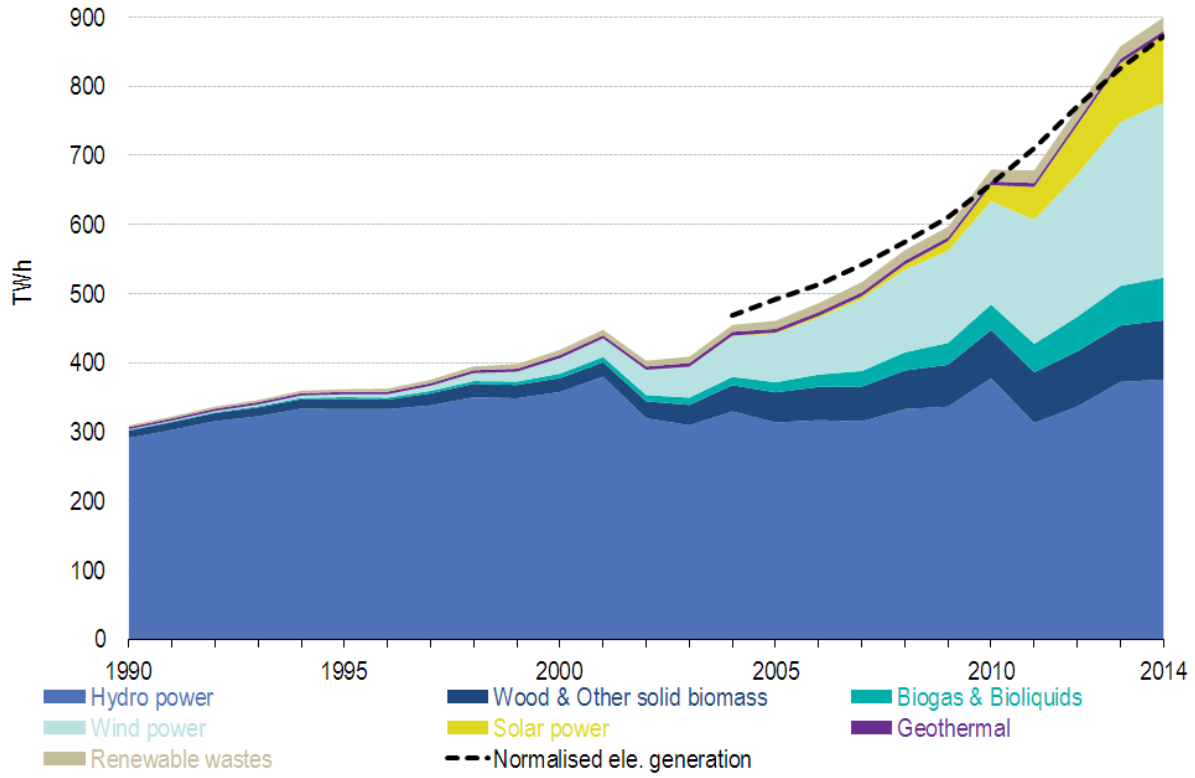


Figure 2-11 Gross electricity generation from RES, EU-28, 1990-2014 (source: Eurostat)

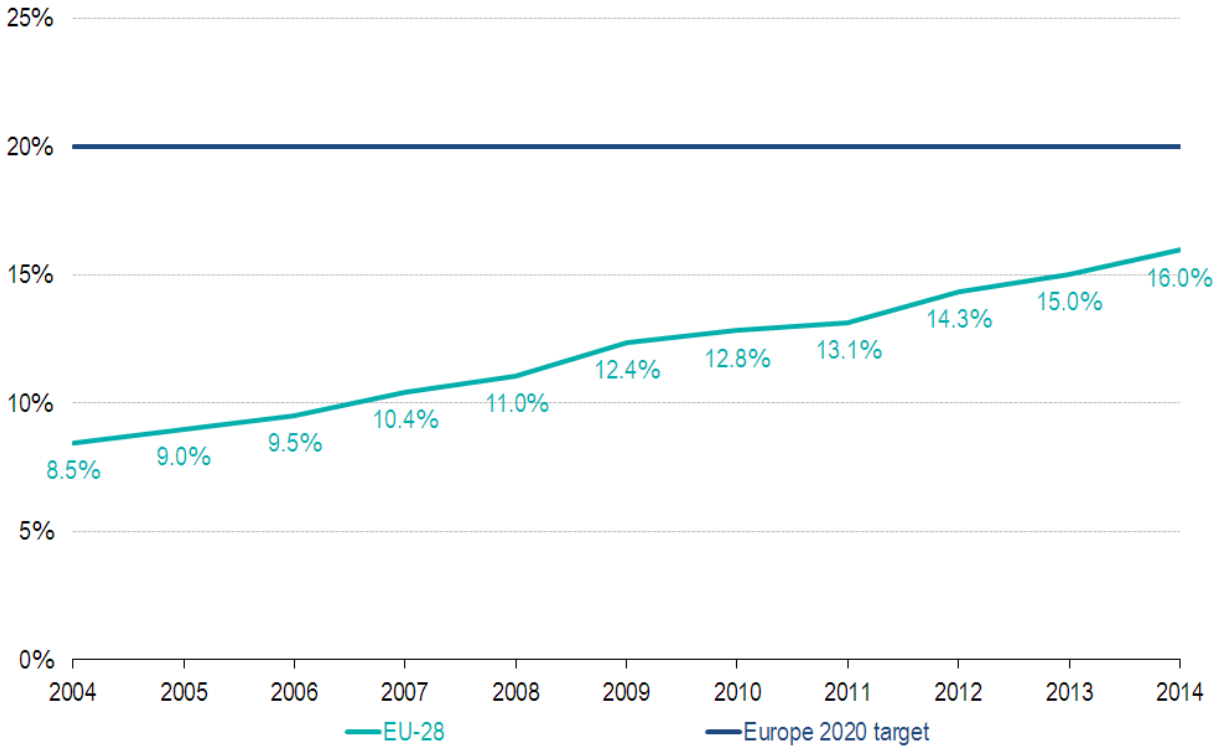


Figure 2-12 Share of energy from renewable sources in the European Union (in % of gross final energy consumption), (source: Eurostat[16]).

[16] http://ec.europa.eu/eurostat/documents/2995521/7155577/8-10022016-AP-EN.pdf/38bf822f-8adf-4e54-b9c6-87b342ead339

In this section are presented some statistical about energy consumption in Europe and Greece and renewables penetration. The European Union (EU) undertakes the completion for 20% of the total energy consumption covered by renewable sources by 2020. This shift from fossil fuels to renewable energy sources it occurs simultaneously with the development of energy use by various transport modes. Aims for state members of EU is to increase the efficiency in energy use and reduce energy demand and attempt as a unity to decouple the last from economic growth. A number of measures in the field are advancement of co-generation, improving energy performance of buildings, and energy labelling for domestic appliances.

As depicted in figure 2-12 it is obvious that the last decade the share of renewables at gross energy final consumption was significantly grew and reached the remarkable 16% in 2014 from 8.5% in 2004. This score is close to achieve the share of 20% for the year 2020.

Table 2-8 Overall share of energy from renewable sources per member in the EU (Directive 2009/28/EC). (source: Eurostat).

		2011	2012	2013	2014	2011-2012 average	2013-2014 average	2020 target
EU28	EU28	13,1%	14,3%	15,0%	16,0%	13,7%	15,5%	20%
BE	Belgium	6,2%	7,2%	7,5%	8,0%	6,7%	7,8%	13%
BG	Bulgaria	14,3%	16,0%	19,0%	18,0%	15,2%	18,5%	16%
CZ	Czech Republic	9,5%	11,4%	12,4%	13,4%	10,5%	12,9%	13%
DK	Denmark	23,5%	25,6%	27,3%	29,2%	24,6%	28,2%	30%
DE	Germany	11,4%	12,1%	12,4%	13,8%	11,8%	13,1%	18%
EE	Estonia	25,5%	25,8%	25,6%	26,5%	25,7%	26,0%	25%
IE	Ireland	6,6%	7,1%	7,7%	8,6%	6,9%	8,2%	16%
EL	Greece	10,9%	13,4%	15,0%	15,3%	12,2%	15,2%	18%
ES	Spain	13,2%	14,3%	15,3%	16,2%	13,8%	15,8%	20%
FR	France	11,1%	13,4%	14,0%	14,3%	12,3%	14,2%	23%
HR	Croatia	25,4%	26,8%	28,1%	27,9%	26,1%	28,0%	20%
IT	Italy	12,9%	15,4%	16,7%	17,1%	14,2%	16,9%	17%
CY	Cyprus	6,0%	6,8%	8,1%	9,0%	6,4%	8,5%	13%
LV	Latvia	33,5%	35,7%	37,1%	38,7%	34,6%	37,9%	40%
LT	Lithuania	20,2%	21,7%	23,0%	23,9%	21,0%	23,4%	23%
LU	Luxembourg	2,9%	3,1%	3,6%	4,5%	3,0%	4,1%	11%
HU	Hungary	9,1%	9,6%	9,5%	9,5%	9,3%	9,5%	13%
MT	Malta	1,9%	2,9%	3,7%	4,7%	2,4%	4,2%	10%
NL	Netherlands	4,5%	4,7%	4,8%	5,5%	4,6%	5,2%	14%
AT	Austria	30,8%	31,6%	32,3%	33,1%	31,2%	32,7%	34%
PL	Poland	10,3%	10,9%	11,3%	11,4%	10,6%	11,4%	15%
PT	Portugal	24,7%	25,0%	25,7%	27,0%	24,8%	26,3%	31%
RO	Romania	21,4%	22,8%	23,9%	24,9%	22,1%	24,4%	24%
SI	Slovenia	20,2%	20,9%	22,5%	21,9%	20,6%	22,2%	25%
SK	Slovak Republic	10,3%	10,4%	10,1%	11,6%	10,4%	10,9%	14%
FI	Finland	32,8%	34,4%	36,7%	38,7%	33,6%	37,7%	38%
SE	Sweden	49,0%	51,1%	52,0%	52,6%	50,0%	52,3%	49%
UK	United Kingdom	4,2%	4,6%	5,6%	7,0%	4,4%	6,3%	15%
IS	Iceland	71,6%	73,2%	72,2%	77,1%	72,4%	74,6%	64%
NO	Norway	64,8%	65,9%	66,7%	69,2%	65,3%	67,9%	67,5%

The role of each country to this differentiates and the final achievements are shown attable 2-8. Because each member state of the EU-28 has different available energy sources and its own unique market, it is obligated to accomplish its distinctive goals by means of its legally binding 2020 (directive: 2009/28/EC). All members should explain in their plans how they intend to do this. The guidelines are created to cover individual energy targets for electricity, heating and cooling, and transportation, the mix of several renewable technologies, policy measures for national targets, planned statistical transfers and/or cooperative projects with other countries, national policies for the development of biomass resources and measures for the compliance of biofuels energy use with EU's sustainability criteria.

Between the 28 members, some they have already fulfilled their goal and others are furthest away. Greece appears to be in line to achieve its own goal as till now it has reached the remarkable 15.3% share of energy from renewable sources and is close to the requested 18% for 2020 (table 2-8, source Eurostat).

3 DESIGN CRITERIA AND ANALYSIS OF HYBRID ENERGY SYSTEMS

Renewable energy technologies have attracted more attention because of their availability, free of cost production and lower harmful emissions to the atmosphere. Nowadays, renewable energy resources like wind, solar, biomass, geothermal, hydro, wave and tides become alternatives to conventional. But to overcome the fact that renewable energy systems are less competitive than convectional, due to the intermittency and uncertainty of renewable resources, and produce energy under the constraints of reliability, sustainability and economic viability a modified configuration that integrates different resources must be implemented. These systems that use more than one resources are called hybrids and could be a combination of renewable and/or conventional resources. Hybrids main target is to utilize their operating characteristics and improve system performance and efficiency.

Most distant sites with hybrid systems for electrification have prioritized solar energy because of its availability. Due to the fact that solar energy is inadequate, the problem of the reliability of a PV system is solved by hybridization. The design of such systems strongly depends on the weather conditions and the availability of other energy sources at the consideration area. Main objective of a project always remains to create a reliable system that meets the load demand with the perspective to be cost-effective.

Wind is preferred as a second renewable source at buildings sector for the generation of electricity, where the wind speed potential technically allows it. Usually wind speed is low during the summer when sun can provide high energy amounts. Conversely, the wind is stronger in the winter when sunlight is less available. Because of the different peak operating times that these forms of energy (solar and wind) occur it is more likely of a hybrid system to produce power when it is needed. In places that it is not possible to implement for example wind, due to the lack of suitable wind speeds for the wind turbine, it may be used another more reliable and more expensive solution like using a conventional source e.g. a diesel generator. Mostly in isolated or remote areas it is usual to store the energy not consumed in batteries for the periods of the day that production is inadequate.

Finally, in this part are presented two of the most common parts of a hybrid energy system being the batteries, as a storage bank, and inverter for the transformation of DC to AC.

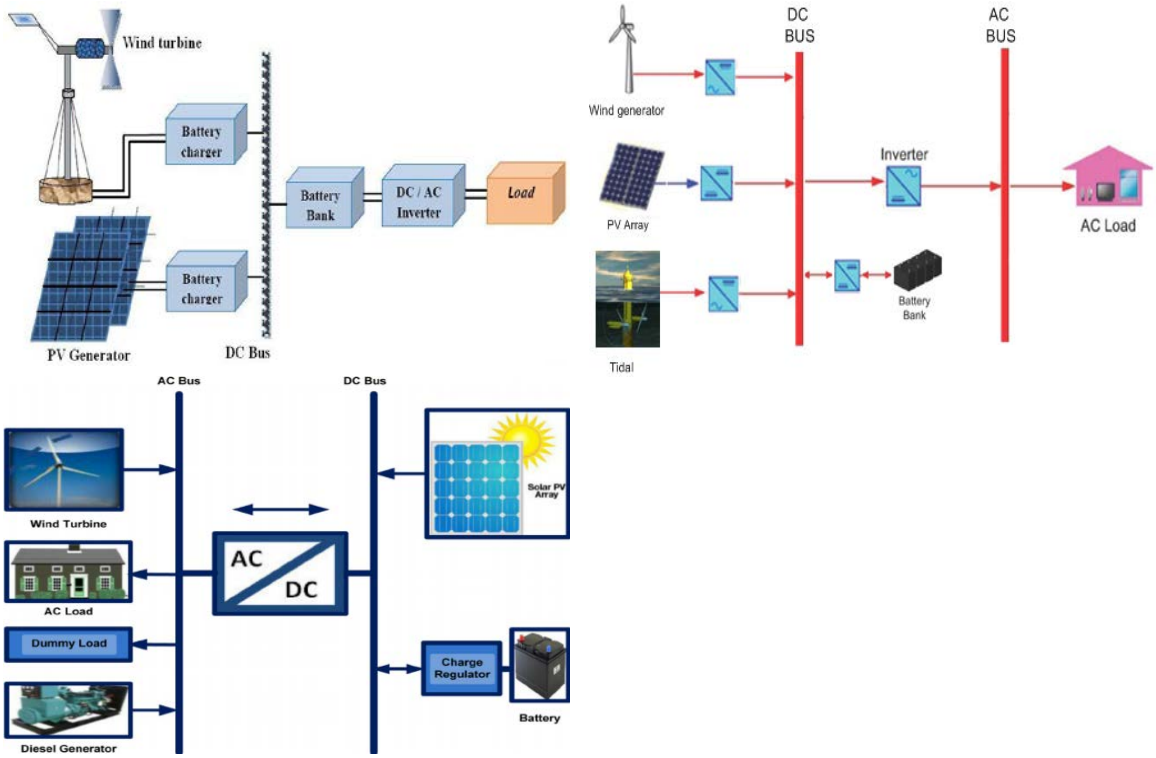


Figure 3-1 A hybrid system for power production may comprise any combination of the above generators which are: a) PV modules, wind turbines and batteries (upper-left corner), b) PV modules, wind turbines, tidal energy and batteries (upper-right corner) and c) diesel generator, wind turbine, solar panels and batteries (lower-left corner).

Usually, building integrated hybrid systems appear to be on-grid, interconnected to the grid utility provider, and when the lack of power appears automatically powered by the grid. Legislation in developed countries, permits consumers to feed electricity they do not use back into the grid. Net metering is adopted as the most recent practice of energy exchange between consumers and public grid utility provider as a billing mechanism that credits private energy produced and added to the grid with that consumed from the grid when the loads exceed the amount of energy provided by the integrated system.

In this part it will be mentioned the different types of optimum sizing methodologies as proposal by some researchers in variant papers [20,21]. Different optimization strategies were adopted depending on the components of the system, control strategy or the cost of the system. Prerequisite for this is a pre-feasibility study of hybrid system.

The requests that should be imported for the design of a hybrid system in general are:

- Meteorological data, for solar radiation and wind speed for the site of interest are necessary in order to optimize the system. If data provided in shortest time intervals (e.g. minutes) then this will result in more accurate solution. In table 3-1 are presented the data that might be provided or synthetically extracted. Data are even obtained from popular databases [22] or synthetically generated. Synthetic data created from monthly-

averaged values or extrapolated from a nearby station. A typical meteorological year (TMY) with hourly values is typically used.

- Load profile, is critical for our system and wrong evaluation of this criteria may lead to system over- or under- size. More often in researches were observed daily or hourly data of loads for the place of interest for the reason that it is difficult to find minute based data. At least yearly loads should be delivered.

After the pre-feasibility analysis, as presented in sub-section 3.3, a plan about the system configuration is designed. So, if in the place of interest low solar radiation outweighs, then it is preferred a hybrid PV-based. Next, the appropriate model for the optimization is chosen to size the components with the constraints of different criteria like LPSP, LLP and etc. in order to achieve the desirable cost and reliability for the system.

3.1 METEOROLOGICAL DATA

Meteorological data acquisition is critical for the sizing and optimization of renewable systems. Available databases, like Meteonorm, PVGIS, SSE-NASA and others (table 3-2), provide data acquired ways, by means of measured, interpolating or satellite estimation data. These data should be obtained with the knowledge of the constraints that mentions here:

- ✓ *Measured data*: different quality measures and different reference years.
- ✓ *Interpolated data*: different densities of grids and different data years.
- ✓ *Estimated data*: different years of data and images that developed, resolution and geometry of images and last the time period of provided data.

Also, before the appropriate database is selected the following uncertainties [23,24,25] must be considered in order to obtain a realistic system for the location under examination.

- ✓ *Transformation uncertainty*: when transforming the information from a satellite image to radiation ranges between 12-13%, for daily base.
- ✓ *Measurements uncertainty*: for the ground stations measured values the quality of data depends on the altitude of the station, the class of the measurement instruments, maintenance and faults procedures contributing to the mean square error around 7-10%, for hourly base data.
- ✓ *Distance uncertainty*: for stations that abstain from the site of interest beyond 15km is estimated to be close to 15%, for hourly base.

Table 3-1 Meteorological data generation.

	Meteorological data generation	Input	Pos	Cons
1	Time series meteorological data	Weather data in hourly basis of solar radiation, wind speed and ambient temperature	Provided raw data and parameters are driven by their variability and consequently design is to be made	Each location require data which is very difficult to found in remote sites
2	Statistical meteorological data	• Weather data are synthetically generated by monthly averaged values or statistically methods used • Weather data created with extrapolation from a neighboring location	Generated in cases of incomplete meteorological data. Reduces computational effort in simulation studies	Less sensitive system to the variation of the parameters

Climatic conditions plays an important role in defining whether the accessibility and scope of solar and wind energy at a specific site. As these data varies continuously and randomly it is obligatory to be characterized in a precise way. In general they divided in two categories of time series and statistical form and table 3-1 clarifies their features associated while handling such types of data.

Table 3-2 Several databases that provide meteorological data.

	Databases	Summary	Web
1	S@tel-light	European database for daylight and solar radiation. Data provided by satellite images since 1996-2000.	http://www.srrb.noaa.gov/surfrad
2	PVGIS	Photovoltaic GiS is Another European database with data acquired for Europe, Africa and Southwest Asia. Obtained by satellite images since 1981-1990.	http://re.jrc.ec.europa.eu/pvgis/index.htm
3	Meteonorm	Global database that contains data from satellite images since 2003-2005 or measured data by ground stations (appr. 7756) since 1981-2000.	http://www.meteonorm.com
4	SODA-IS	Solar Data Intelligent System is also a global database which is linked to several other databases.	http://www.soda-is.com/eng/index.html
5	SSE-NASA	Surface Meteorology and Solar Energy global database. Data derived from satellite images (1985-2004) and ground stations measurements (appr. 1195) since 1964-1993.	http://eosweb.larc.nasa.gov/sse/

Also several databases exist where a studier/researcher could obtain the appropriate meteorological data which are indispensably for the sizing of a renewable energy system. At table 3-2 are presented some of the most popular bases for weather data acquisition.

3.2 DESIGN OF RES IN HYBRID SYSTEMS

As for the design process of the hybrid energy system it requires the selection and sizing of the most suitable combination of energy sources for the case study. It is necessary to choose the appropriate power devices and energy storage system, if it is applicable, together with the implementation of an efficient energy dispatch strategy. Additional to energy sources availability of other factors that should be considered are load requirements such as reliability, efficiency of energy conversion, land requirements, economic aspects, social impacts and even greenhouse gas emissions during the expected life cycle of the system. Briefly, for a given hybrid energy system the design stage it is constituted of the following acts to be determined:

- Type of renewable energy system to be included.
- Size and power output of the units to be installed.
- A back-up unit, like FCs or diesel generator, if should be included in the system.
- If there is a need of energy storage unit to be integrated (essential for stand-alone systems).
- Whether the system under consideration is stand-alone or grid connected.

The availability of the renewable sources of the site is critical for the system selection and then based on the meteorological data (hourly) for the particular site, a feasibility study for different possible configurations by the help of optimization techniques. Several factors or constraints have great influence on the size of system components as for example system reliability or/and economics. Oversizing the system may lead to an unviable economically solution, and at the opposite an under sized system provides a lower initial cost against reliability. Different constraints can be applied, for various loads demand, based on the objectives that should be achieved.

3.3 PRE-FEASIBILITY ANALYSIS

Climatic conditions for a particular site define the disposal and largeness of wind and solar energy for the exact place. Pre-feasibility studies focus on two

basic factors: i) weather data [26] (wind speed, solar insolation, ambient temperature) and ii) load requirements (daily total loads and hourly load allocation). Weather data are provided by widely known meteorological databases like PVGIS, SoDa, NASA SSE, Meteonorm and others or local meteorological stations on the site of interest. Sometimes these data are synthetically generated [27]. Analysis of these data on monthly, daily, hourly or even ten minute intervals is necessary for defining the performance of an existing or under study system. By the use of all these data wind and solar hybrid systems can be determined in a feasible way on site-to-site basis.

The usage of pre-feasibility analysis may lead in a system reduction or differentiation. It is commonness after this procedure a lower battery bank to be produced at stand-alone systems. Also participation rate of photovoltaic and wind generators power may be modulated from place to place with different compound of energy potential. Remarkable studies for the evaluation of the option of hybrid PV/Wind energy systems are reported [28].

In order weather data to be representative for simulations and modeling, data of a full year period were used and statistically analyzed [29]. By this method allows an optimal capacity of the hybrid energy system. A pre-feasibility analysis of a hybrid system for a household with a primary design discussed by Khan and Iqbal [28] and 12 months wind speed, solar radiation and power consumption data were collected to be used to feasibility analysis.

3.4 EVALUATION CRITERIA FOR HYBRID ENERGY SYSTEMS (HES)

With the purpose of an optimum combination for a hybrid system to meet the load demand evaluation should be performed on the basis of power reliability and life-cycle cost of the system. An optimum settlement can be achieved between the parts of the desired system with the adoption of the following objectives: i) power reliability and ii) cost effectiveness of the system.

The intermittent of solar radiation and wind speed is crucial for the power production of a renewable hybrid system. An analysis of power reliability of the system is obligatory at the design process of such arrangements.

A widely used method for this purpose is the Loss of Power Probability (LPSP) [30]. With this it is well described whether our hybrid system power (PV, wind and power bank) is adequate to satisfy our load demand [26]. This method can produce a reliable set of components. Two different approaches are based on this method, first one is based on chronological simulation and requires the availability of data spanning on a certain period of time, mostly for one year. At the other hand a probabilistic approach combines the unstable nature of the resource and load. This technique eliminates the need for time-series data.

Other techniques also used are the *Loss of Load Probability* (LLP) which gives the time period (measured in hours or days) that the power supply of the system fails to reach the load demand, *System Performance Level* (SPL) [31] defined as the probability that load cannot be satisfied and *Loss of Load Hours* (LLH) [32]. Another one is that deals with the risk of loss load (LLR) and decides the proportion of the contribution of each source (PV, wind) [33].

3.4.1 Technical parameters of the power reliability

In this part they will be discussed constraints like LPSP, LLP and SPL, which define the optimal sizing of the system in respect of system reliability.

- LPSP, is defined as the fraction of energy deficit to that required by the loads. As a factor explains the dissatisfaction of the loads in terms of battery charging statement. Another expression is the fraction of total energy losses in a period of time (regularly a year) divided by the load consumption in this period.

  This is expressed by the equation:

$$LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_{LD}(t) \cdot \Delta t} \tag{3.1}$$

  LPS is the loss of power of the system at time *t* and generally can be expressed for a hybrid of a PV/wind/battery system [34,35]:

$$\begin{aligned} LPS(t) = {} & P_{LD}(t) \cdot \Delta t \\ & - \Big(\big(P_{PV}(t) + P_{WG}(t) \big) \cdot \Delta t + C_{bat}(t \\ & - 1) - C_{bat-min} \Big) \cdot n_{inv} \end{aligned} \tag{3.2}$$

  P_{LD} is the power consumed by the load at time *t* and Δt is the time step implemented in the case study. P_{PV} and P_{WG} represent the generated power by the PV/wind generators, respectively. $C_{bat}(t\text{-}1)$ refers to the capacity of the battery before the time *t*, $C_{bat\text{-}min}$ is the minimum capacity of the battery and is the inverters efficiency for the conversion of direct to alternative current.

  Equation (3.1) represents the probability of the load declaration at any moment "t" being lower or equal to the minimal edge of the delivered energy in battery $C_{bat-min}$, and $C_{bat}(t)$ is the energy stored in the battery at any time t [20,36].
- LLP, is the mean load percentage (in large periods of time) not supplied by the PV system, and is expressed as the power failure period to the total working time of the hybrid system [37]. A loss of load occurs

whenever the system load exceeds the available generating and stored capacity. The overall probability that there is going to be a lack of power (loss of load) is called Loss of Load Probability (LLP), and is expressed in terms of days per year, hours per day or even as a percentage of time. Also, when it is referred as the expected accumulated amount of time during which a shortage of power is experienced, the measure is more correctly referred to as the loss of load expectation (LLE).

$$LLP = \frac{T_f}{T} \tag{3.3}$$

where, T_f is the failure time of the system and T is the total examined period of the system. For the times t that the system fails to satisfy the loads by means of eq. (3.4) is negative are add up.

$$\sum_{t=1}^{T} (E_W(t) + E_{PV}(t) - E_L(t)) \; < \; 0 \tag{3.4}$$

where, E_W is the produced energy of the wind generator, E_{PV} refers to the generated energy of the photovoltaics and E_L is the energy demand at time t.

- UL, unmet load, the amount of load that can't be served divided by the total load at that time of period, and calculated as follows:

$$UL = \frac{\sum_{t=1}^{n} P_{failure}}{\sum_{t=1}^{n} P_{total}} \tag{3.5}$$

where, $P_{failure}$ is the load couldn't satisfied and P_{total} is the total load demand.

- LLOR, loss of load risk generally is called the probability of the generating system to failure to meet the daily electrical energy demand due to deficiency energy of renewable generators used and is expressed for a single unit system [33]:

$$LLOR = 1 - p \; or \; LLOR = q \tag{3.6}$$

But if it refers to a system of a PV-wind system then the above eq. (3.6) becomes as follows:

$$LOLR = q_1 q_2 + p_1 p_2 + p_2 q_2 \tag{3.7}$$

where,

p, p_1, p_2 is the probability of success to meet the load demand
q, q_1, q_2 is the probability of failure to meet the load demand

- A, is the level of autonomy and deals with two main parameters i) total number of hours in which the loss of load (H_{LOL}) take place and ii) total operation hours (H_{total})[38]. For higher autonomy system becomes more reliable and more expensive simultaneously.

$$A = 1 - \frac{H_{LOL}}{H_{total}} \tag{3.8}$$

Table 3-3 Criteria and methods for the reliability of hybrid systems

	Reliability Criteria/Method	Definition and representation	Equation
1	Loss of power supply probability (LPSP)	Here probability of inadequate power supply to load is estimated for the system designing and is defined as the ratio of the power deficit to the electric load at a period of time.	$LPSP = \frac{\sum_{t=0}^{n} E_{deficit}}{\sum_{t=0}^{n} P_{load} Dt}$
2	Loss of load probability (LLP / LOLP)	Is given by the portion of time period that system fails and the total working time of the hybrid.	$LLP = \frac{T_f}{T}$
3	Unmet load (UL)	Unserved load at a defined period of time (often a year).	$UL = \frac{\sum_{t=0}^{n} P_{failure}}{\sum_{t=0}^{n} P_{total}}$
5	Loss of load hours (LOLH)	Expresses the total hours system's lack of power during the working period (maintenance and replacement time not in counted).	$LOL = \frac{H_{LOL}}{H_{total}}$
6	Loss of load risk (LOLR)	Rarely used to express the probability of the generators to satisfy the electric load demand.	$LOLR = 1 - p$ $LOLR = q$
7	Level of autonomy (A)	Gives the autonomy of the system and consequently the reliability depending on loss of load and total operating hours.	$A = 1 - \frac{H_{LOL}}{H_{total}}$

3.4.2 System cost analysis

In many researches are mentioned several economic evaluation criteria. Mostly known are net present value (NPV), levelized cost of energy (LCE) and life-cycle cost (LCC) [39].

Net Present Cost (NPC) is defined as the total cost of the system as present value of the initial cost (purchase and installation) with additional the cost of maintenance and component replacements for the project's lifetime, considered to be the life of PV modules as appears to have the longest lifespan. Some costs definitely depend on the control strategy [40]. Also, salvage costs like the

remaining cost of the parts of the system at the end of the project lifetime are considered. NPC is calculated by eq. (3.9) [41]:

$$NPC = \frac{TAC}{CRF} \tag{3.9}$$

TAC is estimated from the present worth of costs (meaning the cost of a future payment or a series of payments discounted to represent the time value of money, e.g. for a hybrid system the present value of costs is formed by the initial costs, the present value of maintenance cost, and the present value of replacement cost) and the capital recovery factor (CRF), eq. (3.10), which is defined as:

$$CRF = \frac{r(1+r)^t}{(1+r)^t - 1} \tag{3.10}$$

$$TAC = PVC \cdot CRF \tag{3.11}$$

where *r* represents the annual discount rate, and *t* is the useful lifetime of the energy system under examination.

Net present cost can also be defined by the following equation:

$$NPC = \frac{TCO \cdot (1+i)^N}{1 + ROI} \tag{3.12}$$

where,

TCO refers to the total capital outlay that concludes initial capital cost, operation, maintenance and replacement costs.

i is the annual inflation rate

ROI is the rate of return of the investment or *MDR* (market discount rate)

N is the cumulative number of years

Important economic factor that also discussed in many researches is the Internal Rate of Return. *IRR* estimates the true interest yield offered by the plant during its operational period and is evaluated by calculating the discount rate that gives net present value (*NPV*), eq. (3.13), equal to zero [42]. Any value greater than zero of *NPV*, the more desirable it to undertake the project. Generally *NPV* is calculated as the difference between discounted present costs of incomes and discounted present costs for the life span of the system [43]. *NPV* is given by the following equation:

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} - C_{inv} = 0 \tag{3.13}$$

$$NPV = \sum NPV_{sale\_k} + \sum NPV_{end\_k} - C_{inv} - \sum NPV_{r\_k} - \sum NPV_{O\&M\_k} \quad (3.14)$$

The aforementioned equations of net present value represent a general formation, eq. (3.13), and a specialized case for hybrids, eq. (3.14) as mentioned by Dufo-Lopez et al [43]. In first case *n* refers to the period of time, C_n is for the cash inflow, C_{inv} gives the cost of the initial investment, and *IRR* represents the internal rate of return. At eq. (3.14) NPV_{sale_k} are the discounted net present values of incomes from e.g. electricity sold to the grid, NPV_{sale_k} are the discounted net present values of the component k at the end of systems life-span, NPV_{r_k} are the discounted present costs of the future replacement of the components (throughout system life-time), and $NPV_{O\&M\_k}$ are the discounted present costs of future costs for operation and maintenance of component k for systems life cycle.

Levelized cost of energy (LCE), is generally defined as the constant price per unit of energy that causes the investment to just break even, and is extensively used for the evaluation of a hybrid PV-wind system configuration [44] and is defined as the ratio of total annualized cost of the components of the system to the total annual energy delivered [21]. Some others approaches mostly used are the levelized cost of system [45] and life-cycle cost. LCE is calculated generally by the following equation introduced by Lazou and Papatsoris [46]:

$$LCE = \frac{TAC}{E_{tot}} \quad (3.15)$$

where *TAC* represents the total annualized cost and E_{tot} the total annual energy.

Life Cycle Cost (LCC) [47], eq. (3.16), is calculated as the whole cost of the hybrid system accounting the initial capital cost IC_{cap}, the present value of replacement (C_{rep}) and operating and maintenance ($C_{O\&M}$) costs minus the remaining value of the components at the end of systems life span.

$$LCC = IC_{cap} + C_{rep} + C_{O\&M} - S \quad (3.16)$$

Salvage value represents the remaining value of the components for the system at the end of the predefined projects lifetime and is calculated by the eq. (3.17).

$$S = \frac{C_{rep} \cdot R_{rem}}{R_{comp}} \quad (3.17)$$

Where, R_{rem} is the remaining life of the systems component at the end of the project life and R_{comp} is the total life of the system component.

Another factor for the economic evaluation of the system is the annualized cost of the system (ACS), eq. (3.18), which is the sum of the annualized capital cost (C_{acap}), the annualized replacement cost (C_{arep}) and the annualized maintenance cost (C_{amain}) [13], and is calculated as it follows:

$$ACS = C_{acap} + C_{arep} + C_{amain} \tag{3.18}$$

An additional economic feature is the payback period (*PBP*) and it refers to the time that the initial cash outflow of an investment is estimated to be recovered by the cash inflows due to the energy production of the system [42].

$$PBP = \frac{C_{inv}}{Cash\ inflow\ per\ period} \tag{3.19}$$

Table 3-4 Cost analysis for hybrid system evaluation.

	Cost analysis	Definition and representation	Equation
1	Net present cost (NPC)	Is the total present value of the cash flows for the system, comprising initial, maintenance and replacement costs within projects lifespan.	$NPC = \frac{C_{ann}}{CRF(i, T_{proj})}$
2	Net present Value (NPV)	Is defined as the sum of incoming and outgoing cash flows over a specific period of time.	$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} - C_o$
3	Life cycle cost (LCC)	Is the sum of all costs over a specified period of time (lifespan) including purchasing, installation, maintenance and replacement costs of all the systems components even salvage value at the end of lifespan or ownership.	$LCC = IC_{cap} + C_{rep} + C_{main} - S$
4	Levelized cost of energy (LCE)	It represents the total annualized cost of the system to the electricity delivered by the system per year.	$LCE = \frac{TAC}{E_{tot}}$
6	Annualized cost of system (ACS)	It is the sum of the annualized costs of the capital, maintenance and replacement.	$ACS = C_{acap} + C_{arep} + C_{amain}$
7	Payback period (PBP)	It is the time period that the initial capital investment is expected to be recovered.	$PBP = \frac{C_{inv}}{Cash\ inflow\ per\ period}$

3.5 OTHER COMPONENTS OF HYBRID ENERGY SYSTEMS FOR POWER GENERATION

A hybrid system for power generation includes also parts for transformation of the electricity from DC to AC and reversely, and additionally the storage systems as the most commonly used are batteries of different types. Next, a short description of these two technologies will be provided.

3.5.1 Inverters for photovoltaics and wind turbines applications

The objective for the use of an inverter device, for grid connected systems or for common household appliances, has two main tasks:

- Invert and amplify the produced direct current (DC) into a suitable alternating current (AC). Hence, PV module generates power approximately 70W to 300W at a voltage around 12V-40V, whereas dwelling appliances require 230V at 50Hz frequency.
- Search for the Maximum Power Point (MPP) of the PV / Wind turbine generators for the maximization of the captured energy.

The above tasks should be carried out in the most efficient way, over a wide power range, due to the daily and seasonally variations and randomness of the renewable energies nature. For that an MPP tracker device is necessary.

Important issue for an efficient inverter is the start-up power to be as low as possible (mainly it spans from 0.15W to 2.5W), which exploits more power by the production system. The power consumption during night time is low, too. In accordance to European regulations [48] the efficiency of the inverter device is calculated as weighted and summed for different percentages of nominal power (5%, 10%, 20%, 30% , 50% and 100%) as presented by the following equation:

$$n_{EU} = 0.03 \cdot n_{5\%} + 0.06 \cdot n_{10\%} + 0.13 \cdot n_{20\%} + 0.10 \cdot n_{30\%} + 0.48 \cdot n_{50\%} + 0.20 \cdot n_{100\%} \quad (3.20)$$

The life of the inverter is depends on the capacitors (electrolytic) included in the system [49], and so the number of the capacitors should be kept low.

3.5.2 Batteries as storage bank for renewable energy systems

Basically, in systems for energy production related to renewable energy sources it is required a storage bank to satisfy the loads when power production is inadequate. It is necessary batteries to be rechargeable. The most common types of batteries are:

- Lead acid
- Nickel cadmium
- Nickel iron
- Nickel hybride
- Lithium (several types)

Lead acid batteries are the most prevalent on such systems. They can reach a depth of discharge over 80% (deep cycle) and rate of discharge less than 3%. Charging/discharging cycles ranging from 500-1000. Their efficiency is depended from the temperature especially at low values.

Nickel cadmium (NiCd) batteries are very competitive to the lead acid due to the higher number of charge/discharge cycles that are between 2000-2500. Discharging rate here is from 2-5%. A great disadvantage of this type is the fact that if they don't fully discharged before recharging, a power reduction occurs. Thus, they are not strongly recommended for the use in renewable energy systems where a variation in production happens all the time.

Batteries are also diverged in two other categories of close and open type. The open type require systematically the supplement of electrolyte and produce less amperes. Close type are separated in AGM and GEL. AGM use Boron-Silicate Glass Mat between the plates and electrolyte is inside the Glass Mat, hence there is no risk of leakage in case of breakage. The rate of discharging is 1-3% monthly and the life expectance 10-12 years. GEL batteries contain the electrolyte in a gel form, who created with the addition of Silica Gel. The deep cycle GEL batteries life ranges close to 10 years.

4 OPTIMUM SIZING METHODOLOGIES

Optimization techniques acts on the sizing design, for example for a PV-wind system, such as in sunny days take full advantage of the PV arrays power and windy days from the wind-turbines. The storage of the excess energy and the sizing of the battery bank is another essential matter that should be handled in an applicable way.

Randomness of wind and solar resources which depend on meteorological conditions became a motivation for different sizing approaches to be born. The necessity of the power maximization simultaneously with minimization of the system cost, causes researchers to verge on different methodologies to achieve that. Several approaches have been reported in literature which can be categorized in two simplified classes, the traditional and new generation approaches.

Traditional methods use a demanding procedure like linear programming, iterative techniques and etc. The second and more modern approaches are genetic algorithm (GA), particle swarm optimization (PSO) and others. Most of these optimum sizing methodologies for PV-wind hybrid systems are briefly described here.

At the present thesis it is proposed an analytical dynamic iterative approach which produces different and accurate solutions, and the procedure is finalized after a significant number of iterations till the best configuration is provided. The adopted iterative method becomes too complicated when several constraints are used and it needs much time to properly created, but it works in a dynamic way if new data imported and defects can be traced at very early stage. Simulations are done with hourly data in order to provide more accurate solutions. Several structural components of the system are considered, like converter, inverter, UPS and batteries as a storage bank. This approach is also compared with a graphical construction technique presented by Markvart [50], as described later. Both methods used in this work are analyzed at section 8.2.

4.1 TRADITIONAL OPTIMIZATION METHOD

In this section will be presented some of the most regular approaches as the most representative. Namely these techniques are linear programming, iterative, graphical construction, probabilistic, and trade-off.

4.1.1 Linear programming technique

Linear Programming (LP) is among the oldest approaches in sizing and optimization of renewable systems. A representative work of this type is Chedid and Rehman [51] research who suggested a method for optimal sizing of a hybrid PV-wind system to meet load demands and minimizing the cost of electricity, taking also into account environmental factors. A new optimization model was proposed by Lee et al [52] considering several power losses. Their model was not based on the minimum cost of the system but its objectives were on the minimum contribution of outsourced electricity supplied and how to keep the battery storage in a minimum amount. About how it impacts the climatic conditions in different places on the sizing of a hybrid plant was discussed by Nagabhushana et al. [53] for three places in Karnataka, India.

4.1.2 Iterative technique

A mathematical process developed that creates different fairly accurate solutions and finishes after a number of iterations when the finest configuration, as per specifications, is reached. It is used for design and optimize. Iterative method obliges more complicated efforts and often a couple of basic parameters for the credibility of the results such as tilt angle of PV generator and wind turbine hub height not took into account in most of the studies.

In this field a research by Yang et al. [21] using LPSP and LCE proposed an optimum solution for a combination of PV-wind generators and resulted in the finest capacity of PV's, wind turbine rated power and battery bank capacity. Another research by Kellogg et al. [54] discussed the wind turbine size and the number of PV modules by the help of iterative optimization. Diaf et al. [20] worked on optimal sizing of all the parts of an autonomous stand-alone hybrid system consisted of PV panels, wind turbines and batteries. This fulfilled under the criteria for the system of reliability and levelized cost of energy.

A remarkable work in this section was done by Prasad and Natarajan [55] and established under the specifications of lack of power supply probability (DPSP), relative excess power generated (REPG), unutilized energy probability (UEP), life cycle cost (LCC), levelized cost of energy (LCE) and life cycle unit cost (LUC) of power generation for a PV-wind system with battery bank. The data used in this research were sunshine duration, solar irradiance, wind speed and load demand distribution for a year, and derived in hourly intervals while the simulation was conducted in daily increments. Several commercially available parts of the system were implemented to find the optimum system individually or with combinations. The inclination of the PVs and the hub-height were considered. Optimal solutions were derived for a specified DPSP under LUC of

generated power or minimum UEP. The developed algorithm can be employed for different locations and even different models of systems components.

Another research that focus on the site of installation, reliability of the system and load profile was proposed by Borowy and Salamaleh [56] of a stand-alone hybrid PV-wind system.

4.1.3 Graphical construction technique

Graphical construction technique is mainly based on long-term meteorological data. The decision making variables that used in this optimization method are solar photovoltaic modules and storage bank or solar PV panels and wind turbine tower. Like iterative method, some crucial parameters that namely are PV modules area and tilt angle, wind turbine swept area and hub height are totally skipped over.

By using a typical load consumption of a house, Borowy and Salameh [56], and the criteria of LPSP and minimum cost of energy provided a correlation between PV array and battery bank.

Also Markvart T. [50] carried out a remarkable research on this method. The criteria of this approach was the demand supply for an integrated system of PV panels and wind turbine. Monthly average values of solar radiation and wind speed adopted for the simulation. The objective function that is used is the minimization of the cost of the system. For the calculation of the system cost he considered the sizes of the two generators multiplied with their cost per unit of power. Summary of these products represents is the cost of the system. Possible configurations are presented in a Cartesian plane with coordinates the sizes of the generators. Various approximations of this technique were derived and the economic analysis showed that the hybrid systems were the most cost-effective solutions for a range of costs.

4.1.4 Probabilistic approach

Probabilistic approach discusses manifold likely results with degrees of certainty/uncertainty of incidence and reflects the random variability of factors. Integrated systems here are created considering solar radiation and wind speed variations. Different models for resource generation and load demand are created and fixed in a combined model sometimes mentioned as “risk model”. A core drawback of this model is that cannot represent the performance of the system in a dynamic way.

Lujano-Rojas et al. [57] created an algorithm for a hybrid PV-wind turbine-diesel generator system using Monte Carlo and Artificial Neural Networks (ANN). They studied the uncertainty of solar energy, wind energy, prices of the

fuels, and life-time of battery bank. Tina et al. [58] worked on the impact of a tracking system, of one or two axis, on the probability density function (PDF) of the PV power output at the first moments (mean, variance, skewness and kurtosis) for a PV-wind integrated system. An analytical model is produced for a long-term performance valuation and also analyzed the improvement energy index reliability (EIR) with the two axis tracker. Finally, their model compared with the results of a time-series simulation model. Karaki et al. [59] also studied an autonomous pv-wind energy system. The sizing of the system was done under the limitation of a superior fixed battery bank in view of charging/discharging cycles for the prediction of expected energy not supplied (EENS).

Yang et al [26] used the criteria of LPSP in order to define the appropriate battery capacity for a PV-wind system. The data used were for a specific year, 1989, and not for a typical meteorological year (TMY) in hourly intervals. For LPSP equal to 0% it was found the most suitable battery capacity was for 5 days and for 1% was a 3 day capacity. Also, less PVs were produced when 3 days batteries capacity was implemented instead of 1. The obtained systems were greatly influenced depending on the portion of LPSP and the power of the chosen WT. Finalizing, Yang observed that the type of system parts, the weather conditions and the profile of the load demand had a great influence on the priority sequence.

4.1.5 Trade-off approach

This approach describes a balance achieved between two desirable but incompatible features; a compromise. Rarely occurs in literature, and mainly as a decision support method for on grid hybrids PV-wind systems based on the aforementioned basic criteria of maximization of reliability and minimization of cost.

Gavanidou and Bakirtzis [60] presented this approach for a stand-alone system, constituted of PV array, wind turbines and batteries as storage, which size is not optimal but the decision is left to the administrator between a set of different vigorous designs. Time series data of solar, wind and loads for the specific site were assumed. Their method is developed to solve the conflict between the minimization of the system cost and the loss of load probability. The uncertainties of wind and solar sources availability, load demand and components reliability were carried out. Considering the uncertainties associated with wind and solar, three scenarios used, two extreme and one intermediate conditions, and nine futures were obtained. Intermediate scenario uses the forecasted averaged values of wind speed and solar irradiance, and extreme values were produced by increasing or decreasing the wind speed by 1m/s or/and solar irradiance by 10%. These resulted in a global decision set that consisted of the union of all conditional decision sets of all futures. Then the obtained trade-off curves created, where each

point represents a plan (a configuration of PV-wind and batteries system), for the associated attributes of the system, cost and LOLP. Resulting, inferior designs were rejected and the decision maker is then is called to make the decision about the "optimum" solution.

Table 4-1 Presentation of different optimum sizing approaches in PV-Wind energy systems.

	Optimisation technique	Important points	Strength	Weakness
1	Iterative approach	Obviously it refers to an iterative process that stops whenever the best configuration is obtained (under evaluation criteria).	Easy in understanding. Defects are traced at early point.	No overlapping phases. Very inflexible.
2	Linear programming	It is based in a model with linear relationships.	Preferred for more complex problems as it is more flexible and simple for most of the rest methods.	Assumptions are unrealistic and linear connection between variables exists. Vary of relation regard to inputs and outputs.
3	Graphical construction technique	Graphical presentation of the solution.	Easy in use.	Not considering some important variables (WT hub height, PV tilt angle).
4	Probabilistic approach	Discuss the system behavior because of the random variability of the effects.	Simple in understanding and use.	No dynamic variation of the performance can be reached.
5	Trade-off method	Negotiates the withdrawal of an aspect in order to gain another.	Understandable in use.	Rarely used in renewable systems applications.

4.2 NEW GENERATION OPTIMIZATION APPROACH

In this section they described modern techniques for sizing and optimizing a hybrid system. The limitation that exist on traditional techniques here can be overcome and global system configuration with relative computation simplicity can be achieved. Traditional approaches on the opposite are mostly used for local configurations.

4.2.1 Genetic algorithm (GA)

Genetic Algorithm (GA) produces solutions as a process that mimics the natural selection and evolution as a result of inheritance, modification and achieving success in a different field or style. Mostly used nowadays because it can solve multivariable problems in an understandable way and which can also be transferred to pre-existing techniques. But the tendency to converge on local optima or unjustified points rather than universal optimum of the problem. Also response times of optimization cannot be confident.

Multi Objective (MO-GA) design is a couple of approaches of GA that one merges all individual objective functions in a single one, and another approach is Pareto [61] optimal approach from a set of solutions to determine the premium. The optimal Pareto solution is the one that prevails between the rests, by improving one objective in conflict with the other.

Koutroulis et al. [62] proposed a GA that provides a balance between the parts of the system and its overall cost, in order to meet the needs of electric energy for a residential building. The proposed optimization algorithm suggests among a list of different commercially available components of PVs, WTs and batteries for a 20 year lifetime. The optimal solution was defined by the right number and type of system parts under the objective function of minimum cost and with the constraint of zero load rejection. Data used to accomplish the simulation were the daily solar radiation on horizontal plane which transposed on the angle of the plane and converted in hourly intervals, the hourly mean values of wind speed and ambient temperature and also the consumers electric load demand for a year, and the simulation was in hourly intervals for a year. The angle of the PVs is set by the user for two discrete period's b1 and b2, b1 contains the months of January to April and September to December and b2 for the rest months, or being constant during all the year. Also, the power law was used for the calculation of the speed at the hub height, and a daily constant but hourly changed load profile was imported. For each combination of system parts the optimum was performed under the constraints of power reliability and minimum system cost, and the obtained systems were listed and the combination with the minimum cost with the corresponding mixture was chosen. The proposed method has the ability to attain the global optimum with a relative computational simplicity, compared to dynamic programming and gradient techniques. Resulting, it was found that hybrid system produced systems with lower cost than exclusively PVs or WTs.

Yang et al. [45] suggested an algorithm for optimization and requested the number of PV panels, wind turbines and batteries simultaneously with PV slope angle and wind turbine tower height for a telecommunication relay station. Bilal et al. [63] used a multi-objective GA to minimize the cost of energy and the LPSP in an annual manner for a PV-wind hybrid system with battery storage. Atia and Yamada [64] preferred a Hybrid Genetic Algorithm (HGA) for their research

which is consisted of double layer GA with a local optimizer for the design and control of PV-wind-diesel systems, and it was proved that HGA is a more powerful algorithm than simplified GA. For a similar hybrid system but with different type of batteries Merei et al [65] used a GA as an optimization mean. Abbes et al. [66] worked with multi-objective GA for a PV-wind plant with batteries and reached a compromised solution between the criteria of loss of power supply probability (LPSP), life cycle cost (LCC) and system embodied energy (EE). Another researcher based on MO-GA was Shi et al. [67] studied the techno-economic performance of a wind-PV system and improved the three objectives of total system cost, level of autonomy and rate of wasted energy using as decisive variables the PV array peak power, the wind generator rated power and the capacity of the battery. Mostofi and Shayeghi [68] proposed a genetic algorithm to simplify the optimization of a PV-wind-hydro-fuel cell multi system. Shadmand and Balog [69] proposed an MO-GA for a PV-wind generators optimization according to the factors of size, cost and availability. Bilal et al. [70] similarly proposed a multi-objective GA for a stand-alone system of tri-generation (PV-wind-diesel) with a battery bank with the criteria of minimum levelized cost of energy (LCE) and CO_2 footprint. For a lifespan of 20 years Tegani et al. [71] generated a GA for a simple PV-wind system.

4.2.2 Particle swarm optimization (PSO)

PSO is a population-based metaheuristic algorithm and attempts to discover the global solution of a problem. Every feasible solution of the problem is called particle and is indicated by a vector which encloses the system variables. Advantages of this method is the high speed for researching and simplicity in calculations. Identified problems are incompatibility with non-coordinate systems and suffers from partial optimism. It is a novice method in hybrids and only few researches are reported.

Basir and Sadeh [72] proposed a system of PV, wind and tidal energy using PSO and compared the cases with or without tidal energy contribute to the system for a 20 year operation. They used data of solar irradiance, wind speed and water velocity in hourly intervals for the simulations. The objective function was the minimizing of the investment cost, replacement, maintenance and operating costs and the economic term used for the calculations was Net Present Cost (NPC), under the constraint of Equivalent Loss Factor (ELF) as the reliability level index, which was set equal to 0.1. Produced systems were also evaluated with different water velocities. The proposed system revealed that the more economic combination was when tidal donated energy to the system.

Lee and Chen [73] focused on achieving the best result for benefit and cost with the coordination of wind-PV plant. Kaviani et al. [74] created an algorithm to optimize a pv-wind-fuel cell project over a 20 year operation by the aim of

minimizing the annual cost of the system and reliably meet the load demand. Bansal et al. [75] managed to avoid local minimum trap of PSO by using an improved form of particle swarm optimization called meta-PSO for a common PV-wind-battery system. Sharafi and ELMekkawy [76] presented a PSO that addresses the multi-objective problem of a system that consisted of PV modules, wind turbine, diesel generator, batteries, fuel cell (FC), electrolyzer and hydrogen tank. Pirhaghshenasvali and Asaei [77] created an algorithm based on PSO for a stand-alone system PV/wind/diesel generator (DG) and battery bank to obtain the optimum size of each part of the system. Borhanazad at al. [78] also resulted in the best configuration for a PV-wind-DG and battery storage system by the help of multi-objective particle swarm optimization (MOPSO). Maleki and Askarzadeh [79] worked on four heuristic algorithms namely, particle swarm optimization (PSO), simulated annealing (SA), harmony search (HS) and tabu search (TS) for sizing two different systems PV-wind-FC and PV-wind-battery under the restrict to be cost-effective. From all the methods PSO prevailed as the more vigorous and favorable. On a different research by Maleki et al. [80] in three different remote areas in Iran he adopted five forms of PSO {PSO, modified (MPSO), repulsion factor PSO (PSO-RF), PSO with constriction factor (PSO-CF) and PSO with adaptive inertia research (PSO-W)} and three more algorithms namely tabu search (TS), harmony search (HS) and simulated annealing (SA), to study their performance and concluded that PSO-CF was dominated and proposed PV-battery hybrids suitable for the regions of his research.

4.2.3 Simulated annealing (SA)

This method is a generic probabilistic meta-heuristic and acts for the global optimization problem of locating a good estimation to the global optimum of a function in a large examination space. It is often used when the search space is discrete. It can provide an acceptably good solution in a limited time but not the best possible, and as an advantage is the capability to avoid local minima. It can deal with nonlinear models, chaotic and noisy data and much restrictions.

Ekren and Ekren [81] presented a SA algorithm with a goal of minimal cost of a pv-wind-battery system to satisfy a GSM base station load requirements. The decision making variables were wind turbine swept area, PV size and battery capacity. Mean hourly data for the solar irradiance and wind speed for the years 2001-2003 were obtained and ARENA 12.0 analyzer was used to predict their theoretical hourly distribution. The same process followed and for the load demand. Load consumption data were acquired in 15 days per season in hourly increments. The objective function was the cost of the system to be minimum and the power constraint was the loss of load probability (LLP) and the level of autonomy (A). The extracted results were better by 10.13% than these produced by Response Surface Methodology (RSM). This methodology can provide also

solutions for various decision variables and at a large search space to optimize the system under examination. Additionally, economic terms like inflation rate and auxiliary generators should be implemented in future researches at the algorithm.

4.3 OTHER NEW GENERATION APPROACHES

Ant Colony Algorithm (ACA) based on the way ants link their colony with a source of food.

Menshsari et al. [82] studied a three generation renewable plant of hydroelectric, pv, wind and hydrogen storage system with the purpose of techno-economic improvement of the system. Xu et al. [83] presented a pv-wind power system by using a specific graph-based ant colony method to minimize the total capital cost under the constraint of the LPSP.

Bacteria Foraging Algorithm (BFA) is a creation that originated by foraging behavior of bacteria.

Bazyar et al [84] presented a BFA for a wind/PV/DG and battery system to cover the load demand for remote rural areas and found it economical viable.

Artificial Bee Colony algorithm (ABC) is based on foraging behavior of honey bee swarm. The simile between the algorithm and bees behavior is that the position of the food characterizes an optimum solution of the sizing and the quantity of nectar is similar to the results quality.

Nasiraghdam and Jadid [85] worked on multi-objective ABC to solve the problem of distribution system reconfiguration of a hybrid system consisted of PV-wind-fuel cell. Also, they extracted the total power loss and electric energy cost while calculating the emissions produced by the plant. Grid minimization and voltage stability index (VSI) maximization calculated too. Maleki and Askarzadeh [86] used artificial bee swarm optimization (ABSO) for a wind-pv-fuel cell system in Iran and found between the combinations pv-wind-FC, pv-FC, wind turbine-FC that the first was the most cost-effective. Tudu et al. [87] observed by using bee algorithm that between the possible configurations of a PV-wind-hydro-fuel cell the one that appeared with the best net present cost used a combination of wind turbine-hydro and fuel cell, in order to cover the load demand of a village in India. Maleki and Pourfayaz [88] optimized a PV-wind-battery system that satisfy a load demand with the minimum annualized cost. Having this system they evaluated the performance of seven optimization algorithms PSO, TS, SA, improved PSO (IPSO), improved HS (IHS), improved harmony search-based SA (IHSBSA), and artificial bee swarm optimization (ABSO) which found to be the most promising of all.

Biogeography-Based Optimization (BBO) optimizes a problem by sustaining a population of contestant solutions and creates new contestant solutions by the combination of the obtainable ones according to a simple

procedure. It is a metaheuristic method. It includes many variations and works without assumptions and so it is widely applicable.

Kumar et al. [89] presented their work with BBO algorithm for a PV-wind-diesel-battery system under the criteria of reliability and economic viability in a region in India. Furthermore, they made a comparison between BBO, GA, PSO, comprehensive learning PSO (CLPSO) and ensemble of mutation and crossover strategies and parameters in DE (EPSDE) algorithm and HOMER software. The results shown that BBO algorithm is faster and gives minimum cost compared to others. Gupta et al. [90] also obtained the optimal design with a BBO of a pv-wind-diesel-battery and the meteorological data for solar and wind obtained by Back Propagation Trained Artificial Neural Network (BPTANN) using time-series forecasting methods and concluded that forecast of resources has great influence on optimal sizing algorithm performance.

Harmony Search (HS) algorithm is revealed by the improvisation process of jazz musicians.

Maleki and Askarzadeh [91] worked with the discrete HS (DHS) and discrete SA (DSA) for different combinations of hybrid systems (pv-wind-diesel-battery, wind-diesel-battery, pv-diesel-battery and diesel) for the most cost effective system. Wind-diesel and battery system proved to be the most viable and DHS algorithm had better performance than DSA.

Gravitational Search Algorithm (GSA) based on second law of motion and Newton's law and found to be superior to traditional optimization algorithms as talking about the precision of the results and convergence speed.

Wu et al. [92] presented the enhanced gravitational search algorithm (EGSA) on a pv-wind-battery system and optimized the power generation and cost of a large scale system. After he compared the results with these obtained by ANN and PSO algorithms and concluded in a lower unit cost power system with EGSA.

Imperialistic Competitive Algorithm (ICA) revealed by imperialistic competition. It consists of an initial population called country and divided into colonies and imperialists which together form empires, being the basis of ICA.

Gharavi et al. [93] proposed a system PV-wind-electrolyzer-fuel cell either autonomous or not with economics, reliability and environmental emissions factors. Fuzzy logic used for multi-objective problem solving and then the system optimization achieved with ICA. Ranjbar and Kouhi [94] proposed a hybrid pv-wind-fuel cell system and optimized with three different methods, GA, PSO and ICA to minimize the total cost. It is called to meet the thermal and electrical demands in three different cases and multiple source systems prevailed and all algorithms results were similar.

Tabu Search (TS) algorithm is an iterative procedure that starts from a random initial solution and tries to find a better solution escaping local optima.

It was proposed by Glover [95], and tabu list and aspiration have significant effect for escaping local optima.

4.4 HYBRID ALGORITHM OPTIMIZATION TECHNIQUES

Hybrid algorithms represent a blend between different types of algorithms in order to take the advantages of each one used in an optimization problem. This section grows up with high rates.

Katsigiannis et al. [96] used a hybrid algorithm (TS and SA) trying to resolve the combinational optimization problem by using as objective function the minimum cost of the system and the variables were: pv array and wind turbine size, biodiesel generator size, diesel generator size, fuel cells size, batteries size, converter size and dispatch plan. For the simulation time intervals were equal to 10min, and system lifetime and discount rate assumed 25 years and 5%, respectively. In order to fulfil the objective function of the minimization of the systems cost of energy (COE), the constraints of initial cost of the system, the annual unmet load fraction, the annual capacity of the storage fraction, the fuel consumption of the generator, minimum renewable fraction, and maximum allowable size of the system components. Annual series data of wind speed, solar radiation, ambient temperature and load consumption, component characteristics, constraints and parameters like project lifetime and discount rate were used as an input to the algorithm. When the simulation was finalized the best combination was then calculated on economic terms of life cycle cost (LCC) of the system and taking into account the annual results of the system, maintenance and replacement costs of system parts and fuel cost of each component, lifetime of system parts, project lifetime and discount rate. All scenarios used include modifications of 10% increasing and decreasing of wind speed, 5% increasing and decreasing of solar radiation, installing two axes tracking system, 20% increase of load demand, increase of diesel fuel price by 20% and 50% cost reduction of renewable technologies. The research showed better results for hybrid than each algorithm individually regards to quality and convergence results. More specifically, SA presented a faster convergence on the optimum area solution, although TS was found more efficient in finding the best solution in the area.

Askarzadeh [97] proposed three algorithms functioning as one and created an innovative chaotic harmony search-based simulated annealing (DCHSSA) algorithm in order to reduce hybrid system cost by minimizing pv array, wind turbine and batteries bank. Tutkun [98] in his research created a Binary Code GA (BCGA) algorithm that minimizes the cost of a pv-wind system and a Support Vector Machine (SVM) for power scheduling regression method. Khatib et al. [99] technique uses an iterative process to extract all the possible configurations of a pv-wind system and then is optimized then by using a GA under the constraint of loss of load probability (LLP) and by achieving reduced system cost. Dehghan et al. [100] studied a pv-wind system and proposed a hybrid algorithm consisted of PSO and HS to increase system power reliability and minimum cost. Zhou and Sun [101] used an SA with PSO hybrid algorithm for a PV-wind with super

capacitor system with criteria of utilization rate and reliability of power supply. Objectives of this algorithm were low initial investment cost and minimum operational costs. The behavior of the hybrid algorithm shown that it is faster and more effective than classic PSO. Abdelhak et al. [102] with a Fuzzy-Adaptive GA managed minimum cost that meets the load demand to obtain the optimum size of a PV-wind-battery system. They proved moreover that it acts better than the regular GA. Mukhtaruddin et al. [103] presented an Iterative-Pareto-Fuzzy (IPF) and obtained a PV-wind system with batteries and reached a minimum cost with high reliability compromise. One last approach that should be mentioned is Alsayed et al. [104] Multi Criteria Decision Analysis (MCDA) algorithm as a mixture of MOGA and Multi Criteria Decision Making (MCDM) for optimizing a grid connected PV-wind system.

4.5 COMPUTATIONAL SOFTWARE FOR ENERGY SYSTEMS SIZING

Many computer software have been developed for professional designers and constructors. The simplicity of such tools serves the rule of everyday use by just importing some data and do some short scale customization. Mostly, extracted results rely on net present cost and power reliability. Some commercial sizing tools and their features are proposed on table 4-2.

Table 4-2 Commercial & free software tools for hybrid energy systems sizing and optimization.

	Software tools	Input	Output
1	HOMER	• Load demand • Resource input • Details of parts (capital, maintenance and replacement cost) • System Control	• Optimal generator sizing • NPC, COE • Portion of renewable energy
2	RET Screen	• Load data • Climate database • Size of solar array • Required hydrology and products database	• Costs • Energy production and savings • Emission reductions • Financial viability • Sensitivity and risk analysis
3	HYBRIDS	• Size of solar array • Wind turbine type • Quantity and type of battery	• COE • Percentage of gas emissions
4	HYBRID2	• Load demand • Resources input • Initial investment and O&M cost of system parts	• Unit sizing with cost optimization • COE

			• Percentage of greenhouse gases emissions • Payback period of the system
5	TRNSYS	• Meteorological data input • Inherent models	• Simulation results of electrical and thermal energy systems
6	IHOGA	• Load data • Resources input data • Components and economics details	• MO optimization • COE • Life cycle emissions • Analysis for buy and sell of energy

5 MATHEMATICAL MODELS FOR OPTIMAL SIZING OF RENEWABLE ENERGY TECHNOLOGIES

5.1.1 Mathematical models for wind generator

Wind speed varies depending on many factors. Most important are the local land terrain, weather system that is used and the height above the ground. Hence it is necessary a model to be produced to capture the existing variations to forecast the energy production. Usually, wind variation is best depicted with Weibull probability density function which best expressed by eq. (5.1):

$$f(v,k,c) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{-(v/c)^k} \tag{5.1}$$

where, *f(k,v,c)* is for the probability of wind speed (*v*), *c* is the scale parameter, *k* is the shape parameter and $v \geq 0$, $k > 1$, $c > 0$.

In this sub-section different methods for the calculation of electric power output of wind generators are presented. The hub height of the WT also is of great importance and is used in accordance with the wind gauge height that wind speed values are obtained [105].

$$\left(\frac{v}{v_r}\right) = \left(\frac{h}{h_r}\right)^n \tag{5.2}$$

where, *v* and v_r represent the wind speed at hub height "*h*" and at reference height "h_r", and *n* is the power law exponent (ranging from 1/7 to 1/4) which depends from elevation, time of day, season, terrain nature, wind speed and temperature.

The power of wind turbine P_{WG} it depends on the rated power output (P_r), the cut-in speed ($v_{cut\text{-}in}$) and cut-out speed ($v_{cut\text{-}out}$). A simplified method for the estimation of power output uses a linear equation as seen at eq. (5.3) [86]:

$$P_{WG}(v) = \begin{cases} P_r \dfrac{v - v_{cut-in}}{v_r - v_{cut-in}} & v_{cut-in} < v < v_r \\ P_r & v_r \leq v < v_{cut-out} \\ 0 & v \leq v_{cut-in} \; or \; v \geq v_{cut-out} \end{cases} \tag{5.3}$$

When the applicable wind turbines differentiates than a single one, then the results from each of the above equations are multiplied with the total number of wind turbines N_{WG}.

The energy that produced per annual E_{an} by the wind generator and it is calculated as:

$$E_{an} = 365 \times 24 \left(\sum_{v=0}^{v_{cut-out}} P_{WT} \times f(v,k,c) \right) \tag{5.4}$$

A quadratic model developed for the estimation of wind generators power output is given by eq. (5.5) next:

$$P_{WG}(v) = \begin{cases} P_r \dfrac{v^2 - v_{cut-in}^2}{v_r^2 - v_{cut-in}^2} & v_{cut-in} < v < v_r \\ P_r & v_r \le v < v_{cut-out} \\ 0 & v \le v_{cut-in} \; or \; v \ge v_{cut-out} \end{cases} \tag{5.5}$$

where wind speed is obtained or adjusted at hub height.

Khatod DK et al [106] expressed the power output of WG mathematically by the following system of equations:

$$P_{WG} = \begin{cases} 0 & for \; 0 \le V < V_{cut-in} \\ aV^3 + bP_r & for \; V_{cut-in} \le V < V_r \\ P_r & for \; V_r \le V \le V_{cut-out} \\ 0 & for \; V \ge V_{cut-out} \end{cases} \tag{5.6}$$

At the above system of equations V_r refers to the rated speed of the wind generator and constants a, b estimated as a function of rated and cut-in wind speeds.

$$\begin{cases} a = \dfrac{P_r}{V_r^3 - V_{cut-in}^3} \\ b = \dfrac{V_{cut-in}^3}{V_r^3 - V_{cut-in}^3} \end{cases} \tag{5.7}$$

The actual power of the wind turbine P_{WT} that is available then is given by eq. (5.8) [107]:

$$P_W = P_{WG} A_w n \tag{5.8}$$

where, A_w is the total swept area, and n is the efficiency of WG convertor and corresponding converters.

Diaf et al [20] used a model for estimating the output power through interpolated values of data obtained from the manufacturer. Then power curves are analyzed using cubic spline interpolation [108]. Wind generators output next is expressed by the following set of equations.

$$P_{WG}(v) = \begin{cases} 0 & v \le v_{cut-in} \text{ or } v \ge v_{cut-out} \\ a_1 v^3 + b_1 v^2 + c_1 v + d_1 & v_{cut-in} < v < v_1 \\ a_2 v^3 + b_2 v^2 + c_2 v + d_2 & v_1 < v < v_2 \\ \dots & \dots \\ a_n v^3 + b_n v^2 + c_n v + d_n & v_{n-1} < v < v_r \\ P_r & v_r \le v < v_{cut-out} \end{cases} \quad (5.9)$$

Here $P_{WG}(v)$ is the power output for wind speed v, P_r is the rated or nominal power, $v_{cut\text{-}in}$ refers at cut-in speed (start working of WT), v_r (nominal power output occurs) and $v_{cut\text{-}out}$ are the rated speed and cut-out (stop working of WT) speed respectively. All velocities adjusted at hub height using the power law, eq. (5.2). Moreover, n represents the number of cubic spline interpolation functions that corresponds to $n+1$ speed and power couples of values. Finally, for a, b, c and d are the polynomial parameters produced for the specific wind turbine. This method can be used and at higher grade in other cases.

Another mathematical model that considers the characteristics of the wind turbine is developed. It appears as a function of dimensionless tip speed ratio (λ) for a horizontal axis turbine [109].

$$P_{WG} = \frac{-\left(C_p \cdot \lambda \cdot \rho \cdot A_w \cdot v^3\right)}{2} \quad (5.10)$$

where, C_p constitutes the power co-efficient and takes values 0.3 - 0.5, ρ is the air density (kg/m^3), A_w the swept area of wind turbine blades (m^2) and v the wind speed (m/sec) at hub height. Tip speed ratio is calculated as follows:

$$\lambda = \frac{\omega \cdot R}{v} \quad (5.11)$$

Here ω is turbines rotor speed in rad/sec and R the radius of the blades (m).

Koutroulis et al [62] used a diagram of the power of WG provided by the manufacturer P_{WG} (Watt) versus v (m/sec) (Power Curve), the output power of the generator can be obtained by a look up table to the optimization algorithm. The effects of charger power conversion and the conversion efficiency of MPPT, if existing, are well thought-out. Hence the transferred power to the battery at hour t of day i is then given by eq. (5.12):

$$P_{WG}^{i}(t,h) = P_1 + \left[v^i(t,h) - v_1\right]\frac{P_2 - P_1}{v_2 - v_1} \quad (5.12)$$

where $v^i(t,h)$ is the wind speed at hub height estimated by the exponential law from eq. (5.2), and pairs (P_1,v_1) and (P_2, v_2) obtained from the look up table.

5.1.2 Mathematical models for photovoltaics

Solar radiation is the input parameter for the PV generator. The photovoltaic panels are generally applied at an angle similar to the latitude of the site under consideration in order to maximize the gains annually. So, the output power of the PV array depends on beam and diffuse radiation that falls on the panel modules.

The output of the PV generator [30] is given in general by the equation:

$$P_{PV} = N \cdot A_{PV} \cdot I_T \cdot n_{PV} \tag{5.13}$$

where n_{pv} is the PV module efficiency, A_{PV} is the summarized area of PV modules and I_T is the solar radiation on the inclined PV module expressed in W/m^2 and N is the number of modules of PV array. The efficiency of the PV module it depends on ambient temperature T_a, module efficiency n_m and maximum power point tracker efficiency n_{MPPT} which will be thoroughly analyzed later.

Hongxing Yang et al [21] in his optimization model approaches the power output of the module by a regression model which is specified as follows, eq. (5.14):

$$P_m = -(a \cdot I_T + b) \cdot (T_a + 0.03375 \cdot I_T) + c \cdot I_T + d \tag{5.14}$$

$$P_{PV} = N_{PVP} \cdot N_{PVS} \cdot V_{PV} \cdot I_{PV} \cdot F_{con} \cdot F_{oth} \tag{5.15}$$

where, I_T is the total solar radiation that incidents on the module (W/m^2), T_a is the ambient temperature, and a, b, c and d are constants of the regression model for the PV element. The parameters for this model can be extracted from on-site tests. As for P_{PV} expresses the power output of the array, where the number of modules in series (N_{PVS}) and in parallel (N_{PVP}) strings are considered, including cable losses (F_{con}) and others (F_{oth}). V_{PV} and I_{PV} are the voltage and the current of the whole generator.

Zhou et al [110] at his research used a five parameters (α, β, γ, R_s, and n_{MPPT}) model for the PV module performance with respectable precision under varying conditions. All these are prescribed at the following equation that considers the fill factor:

$$P_m = \frac{\frac{V_{oc}}{n_{MPP}\,KT/q} - \ln\left(\frac{V_{oc}}{n_{MPP}\,KT/q} + 0.72\right)}{1 + \frac{V_{oc}}{n_{MPP}\,KT/q}} \cdot \left(1 - \frac{R_s}{V_{oc}/I_{sc}}\right) \cdot I_{sco}\left(\frac{G}{G_0}\right)^{\alpha} \cdot \frac{V_{oco}}{1 + \beta \ln\frac{G_0}{G}} \cdot \left(\frac{T_0}{T}\right)^{\gamma} \quad (5.16)$$

where,

n_{MPP} is the ideality factor at MPP ranging from 1 to 2

K is the Boltzman constant equals to 1.38×10^{-23} J/K

T is modules temperature (K)

q represents the magnitude of the electron charge, 1.6×10^{-19} C

R_s is the series resistance (ohm)

α is a factor that represents all the nonlinear effects that photocurrent depends on

β is a coefficient related to the PV panel technology

γ is a factor that expresses the nonlinear temperature-voltage effects

G, G_o are solar irradiance intensities for real and STC conditions respectively.

So, considering also the efficiency of the maximum power point tracking (MPP) system, n_{MPPT}, then the PV unit power output estimated from eq. (5.17) [45]:

$$P_{PV} = N_{PVP} \cdot N_{PVS} \cdot P_m \cdot n_{MPPT} \cdot F_{oth} \quad (5.17)$$

Anula Khare et al [111] they were used technical parameters of the PV module under consideration which are proportional of the short circuit current (I_{sc}), the open circuit voltage (V_{oc}), and finally the fill factor (FF) as seen under (eq. (5.18)):

$$P_m = V_{oc} \cdot I_{sc} \cdot FF \quad (5.18)$$

where the fill factor (FF) is the fraction of power at the MPP to the maximum power that can be reached by a module and given as follows:

$$FF = \frac{V_m \cdot I_m}{V_{oc} \cdot I_{sc}} \quad (5.19)$$

As for the electrical characteristics of the module, referring to I_{sc} and V_{oc}, they are modified from STC (standard test conditions) to real conditions by the help of the following set of equations:

$$\begin{cases} I_{sc} = [I_{sc}(stc) + K_i \cdot (T_c - 25)]\dfrac{I_T}{1000} \\ V_{oc} = [V_{oc}(stc) + K_v \cdot (T_c - 25)]\dfrac{I_T}{1000} \\ T_c = T_a + \left(\dfrac{NOCT - 20}{800}\right) \cdot I_T \end{cases} \quad (5.20)$$

Where K_i and K_v are the temperature coefficients for I_{sc} (Ampere/Kelvin) and V_{oc} (Voltage/Kelvin) respectively; T_c is the temperature of the cell and *NOCT* is the nominal operating cell temperature given by the manufacturer.

Kaplani E. et al [112] at her research considers a significant number of losses in a PV system that may lead to a failure. Of great importance is also the factor *d* which represents the days of autonomy [113] for the system due to the inherent fluctuation of solar radiation. The peak power is then given by:

$$P_m = \frac{d \cdot Q_L \cdot F}{PSH_m \cdot R_m} \quad (5.21)$$

$$F = C_{T_C} \cdot C_{ch} \cdot C_{inv} \cdot C_{bat-ch} \cdot C_{PV-ageing} \quad (5.22)$$

$$\begin{cases} d_{cr} = -1.9 \cdot PSH_{min} + 18.3 \\ d_{n-cr} = -0.48 \cdot PSH_{min} + 4.58 \end{cases} \quad (5.23)$$

Where Q_L are the loads divided in two main categories, critical and non-critical, as prescribed in eq. (5.23), PSH_{min} is the minimum value of peak solar hour (PSH). Critical loads require more power, at least 99%, of the total annual demand instead of non-critical which require 95%. PSH_m is the mean value of PSH (h/day), R_m is the a conversion factor for the global solar radiation from horizontal to inclined plane, *F* refers to the different power losses occurred in a PV generator, namely C_{Tc} is an improvement factor due to the temperature effect on PV efficiency, C_{ch} refers to the charger efficiency, C_{inv} is for the inverter efficiency, and C_{bat-ch} is for the efficiency of the battery during charging process. PV ageing is also counted, $C_{PV-ageing}$.

Another approach by the authors [114] in eq. (5.21) uses additionally a correction term for more accurate estimation of PV's power output regarding to the fluctuations of the average solar radiation, H_m and expressed by:

$$P_{m,cor} = Q_L \cdot F \cdot \left(1 + \sqrt{d} \cdot 2 \cdot \sigma_H / H_m\right) / (PSH_m \cdot R_m) \quad (5.24)$$

Where, σ_H is the standard deviation for solar radiation, *H*, on a particular day n_j.

5.1.3 Mathematical models for battery bank

Batteries are a crucial component especially when talking for stand-alone systems. In general, for the optimization of hybrid systems they were used either for the calculation of the batteries capacity (C_L) or the state of charge (*SOC*). The maximum state of charge is 1 and minimum is the difference SOC_{min}=1-DOD. Depth of discharge (*DOD*) is the energy that the battery can provide and differentiates depending on the type of the battery. Here are provided different mathematical relations that used for the estimation of the capacity and for the state of charge during training/testing process in many researches.

Kaplani E. et al [115] worked with a conventional approach and used days of autonomy, *d*, in order to estimate battery capacity. This methodology provided a good reliability for the system but it also leads to a larger system estimation. The equation that is used is shown under:

$$C_L = \frac{d \cdot Q_L \cdot F'}{V \cdot DOD} \tag{5.25}$$

where F' is the correction term for the transfer power losses and V is the transfer voltage. Autonomy days *d*, is described in previous subsection and given by equation (5.23), and depends on the kind of loads to be satisfied.

The fact that from the above equation the size of the system is overestimated a correction factor was introduced and evaluated. This resulted in a significant decrease of the system.

$$C_{L,d} = C_L \left(1 + \frac{2\sqrt{d} \cdot \sigma_H}{H_m(n_j)}\right) \tag{5.26}$$

Furthermore, the nominal capacity of the battery it is influenced by different factors during the lifetime. In summary these are, the number of years of the battery (t_b), the correction factor due to cycles (C_c≈0.007-0.01), and the ageing of the battery (C_a≈0.014-0.02). Altogether, are expressed in the nominal capacity (C_N) as described in the next equation:

$$C_N = \frac{C_L}{1 - t_b \cdot (C_c + C_a)} \tag{5.27}$$

Hongxing Yang et al [21] in their research consider the SOC as two different processes of charging and discharging. Consequently, this leads to the following relations where the only difference that appears is the implementation of battery charging efficiency, n_{bat}.

$$\begin{cases} SOC_{ch}(t+1) = SOC(t) \cdot (1-\sigma(t)) + \dfrac{I_{bat}(t) \cdot \Delta t \cdot n_{bat}(t)}{C_{bat}} \\ SOC_{dis}(t+1) = SOC(t) \cdot (1-\sigma(t)) - \dfrac{I_{bat}(t) \cdot \Delta t}{C_{bat}} \end{cases} \quad (5.28)$$

where $\sigma(t)$ is the hourly self-discharge rate and proposed to be 0,02% approximately. I_{bat} is the charging/discharging current at time t, and C_{bat} is the battery capacity (Ah). SOC values are ranging between 0 and 1. Value 1 declares that batteries are fully charged.

Berndt D. [116] estimated the battery capacity as a function of the batteries working temperature, T_{bat}, and temperature coefficient δ_c, usually 0.6% per degree or provided by the manufacturer. This equation is given under:

$$C'_{bat} = C''_{bat} \cdot \left(1 + \delta_c \cdot (T_{bat} - 298.15)\right) \quad (5.29)$$

C_{bat}' and C_{bat}" represent the battery capacity for temperature T_{bat} and nominal capacity, Ah, respectively. Hence, it can be simply calculated the SOC of the battery at any time t, using the current that flows through the system, for the charge/discharge process by eq. (5.28). The appropriate losses are considered when estimating P_{PV} and P_{WG}, and both imported at I_{bat} (A) equation.

Diaf S. et al [30] estimates the battery bank capacity at the time t depending on charging or discharging. Hence, the following equations are used in each case:

$$C_{bat}(t) = C_{bat}(t-1) + \left(P_{PV}(t) \cdot n_{cdd} + P_{WT}(t) \cdot n_{acd} - \frac{P_L(t)}{n_{inv}}\right) \cdot n_{cha} \cdot \Delta t \quad (5.30)$$

$$C_{bat}(t) = C_{bat}(t-1) + \left(\frac{P_{PV}(t) \cdot n_{cdd} + P_{WT}(t) \cdot n_{WT} - \frac{P_L(t)}{n_{inv}}}{n_{dech}}\right) \cdot \Delta t \quad (5.31)$$

where at the above equations C_{bat} represent the Wh of the battery during the charge and discharge process at times t and t-1. In both equations (5.30) & (5.31), the primary source for the hybrid system considered to be the PV. Here, n_{cdd} and n_{acd} are the efficiencies for DC/DC converter of the PV and AC/DC converter of the WG, in that order. As for n_{inv} is inverters efficiency and n_{dech} is the efficiency of discharging process. When the batteries are charging it is also taken into account and the charging efficiency, n_{cha}.

Bogdan and Salameh [34] presented a model to estimate the capacity of the battery considering the influence of batteries self-discharge rate (σ). The two conditions of charging and discharging are given under:

$$\begin{cases} C_{bat}(t) = C_{bat}(t-1)\cdot(1-\sigma) + \left(E_{PV}(t) + E_{WG}(t) - \dfrac{E_{LD}(t)}{n_{inv}}\right)\cdot n_{bat} \\ C_{bat}(t) = C_{bat}(t-1)\cdot(1-\sigma) - \left(\dfrac{E_{LD}(t)}{n_{inv}} - E_{PV}(t) - E_{WG}(t)\right)\cdot n_{bat} \end{cases} \quad (5.32)$$

when the energy produced by the PV (E_{PV}) and wind turbine (E_{WG}) is greater than the load demand (E_{LD}), charging, then the efficiency of the battery, n_{bat}, averages between 0.65-0.85, or else it equals to 1, discharging. The self-discharge rate holds to be 0.14% per day. The efficiency of the inverter (n_{inv}) regularly approaches 92%.

The mathematical models used and the followed methodology will be analyzed at chapter 8.

6 SYSTEM CONTROL MANAGEMENT

A regular problem that often appears between the interaction of RES and load consumption is the stability of the provided energy and the frequency and voltage of the current. In such cases, to overcome these kind of problems systems that manipulate delivered energy are used, so called energy control systems. For this process two stages are accomplished. Firstly, energy sources and load demand prediction are determined and afterwards energy sources and back-ups (batteries, fuel cells and etc.) are optimized to provide the appropriate energy flow. This type of systems categorized in three basic categories: *centralized control arrangement, distributed control arrangement and hybrid centralized and distributed control arrangement*. A slave controller is placed locally on every renewable generator to optimally deliver energy to the loads, based on current information.

6.1.1 Centralized control arrangement

Commonly used on multi-objective energy management systems and it works on global optimum converge based on obtainable data. About the operation of this method, it counts on a master controller that communicates with the slave controllers (one for each renewable energy) and acts as a supervisor. It decides whether a source can be used, always depending on some prearranged objectives and constraints. Disadvantages of this control system is computational time, which is pretty high, and single point failures.

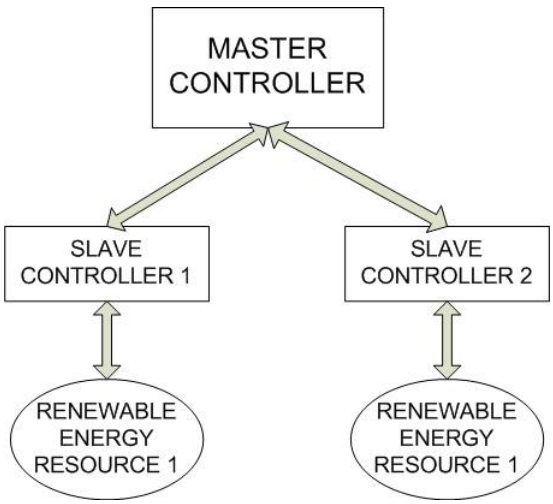


Figure 6-1 Centralized control arrangement.

6.1.2 Distributed control arrangement

On opposite of centralized control arrangement, here the decision is made by local controllers, and after an interaction between all of them (each one connected to a renewable source), global optimization can be achieved and avoid any single point failures. Computational time is strongly reduced. As a drawback can be accounted the communication between controllers that is complicated, and this is overwhelmed by using artificial algorithms such as ANN, GA, hybrid ANN-GA or the most promising Multi-Agent System (MAS).

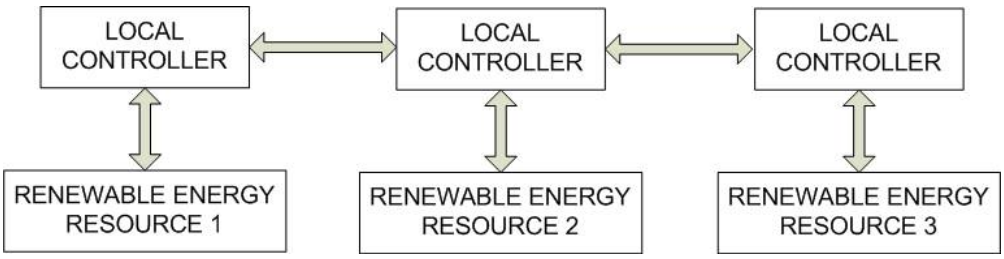


Figure 6-2 Distributed control arrangement.

6.1.3 Hybrid distributed and centralized control arrangement

Hybrid system exploits the advantages of its aforementioned method, namely centralized and distributed. Centralized control is applied to each group and distributed coordinates them, so local and global optimum is achieved respectively by each arrangement. As results, less time is required and minimizes single point failures.

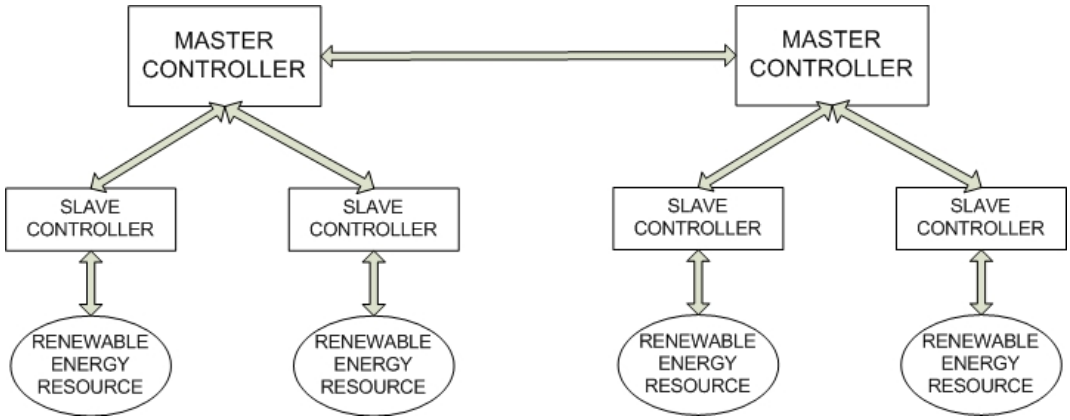


Figure 6-3 Hybrid centralized and distributed control arrangement.

Literature that deals with energy flow management is in abundance. Remarkable research was done by Torreglosa et al. [117] who proposed a hierarchical control system with a master and slave control strategy for integrated system. The decision criteria for the source that contributes to the load demand is the cost of produced energy and this judgment is done by master control system.

A different approach on energy flow management was done by Malla et al. [118] who managed to supply the AC load constantly by the control of DC link voltage modulation index of a PWM inverter. Maximum Power Point Tracker (MPPT) was used in PV array. Das et al. [119] presented PI/PID controllers[17] that adjust the output power from the generators and minimized the mismatch among load production and consumption under varying conditions and reduced the frequency deviation (Df) by the help of GA controllers. Its behavior was better than automatic generation control from the viewpoint of peak transient deviation and settling time.

Table 6-1 Energy control management in RES.

	Type of control	Summary	Pros	Cons
1	Centralized control	The measurement signals of all generators delivered in a group to the controller.	For global optimization by multi objective energy management system.	Encumbrance of heavy computation and possible single-point failures.
2	Distributed control	Each energy has its own (local) controller where measurement signals are provided.	It appears with low risk for single point failures as computation weight of each renewable part of the system is reduced.	Complexity for local controllers of the system to communicate.
3	Hybrid control (Centralized & distributed)	Exploits local optimization via centralized control within each group, whereas distributed control coordinates different groups globally.	Local controllers depressurized computationally and single point failure risk is minimized.	Possible communication complexity.
4	Multilevel control approach	Similarly to hybrid control centralized control is used for the optimization of each group and distributed control for total coordination between groups.	Single-point failure problem is tempered. Dual way communication is achieved for different levels in order to obtain a decision.	Composite is probable for the communication of the system.

[17] ***PI*** controllers are fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral term may prevent the system from reaching its target value due to the control action. A ***PID*** controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable.

7 DATA ACQUISITION FOR THE SITE AND SYSTEM COMPONENTS

A stand-alone hybrid system, that consists of PV/WT generators and batteries banks, in order to provide electric energy in a detached dwelling, is investigated. The location of the house is at Rhodos island, Greece. The steps that will be performed for the purpose of creating a reliable and viable system are by following series; hourly meteorological data acquisition and analysis of the solar radiation, wind, and ambient temperature; hourly load consumption profile of the dwelling; simulation of the obtained system and evaluation under the defined technical evaluation criteria namely LPSP and LLP; and finally the economic optimization of the system shall be done in terms of LCE and NPV. The quality of wind and solar data in hourly, daily and monthly intervals will also be investigated.

Several factors or constraints directly influence the sizing of the system components e.g. system economics, and system reliability. Over sizing of the components may lead to high system cost and therefore, the system may become economically unviable. On the other hand, under sizing will reduce the initial cost but a there must be a compromising with the system reliability. For a particular load, different constraints may be applied to the set of system components based on the objectives that have to be achieved.

Also the comparison of different approaches namely iterative technique and graphical construction technique will be thoroughly presented in order to obtain a system which will accomplish the reliability and economic viability of the system. Therefore cons and pos of each method will be analyzed and that considers better the system behavior will be further investigated. Next, the choice of the best system type by meaning PV only, WT only or hybrid system it is provided,

Right after the effects of different factors like the use of two different power evaluation criteria, namely Loss of Power Supply Probability (LPSP) and Loss of Load Probability (LLP) are studied.

At last, an evaluation of the systems produced for the two formation, with and without UPS, of the systems parts is done. This process is done for different load profiles and with different LPSPs.

7.1 QUALITY OF METEOROLOGICAL DATA

Meteorological data acquired from Meteonorm database for the site of interest, Rhodos island, Greece, in hourly intervals of wind speed (m/sec),

ambient temperature (ºC) and global solar irradiance on horizontal plane. No missing data were found. The hourly solar irradiance was converted to 36º angle of inclination and wind speed data translated to 23m at hub height, from the reference height 10m, using the power law, eq. (5.2).

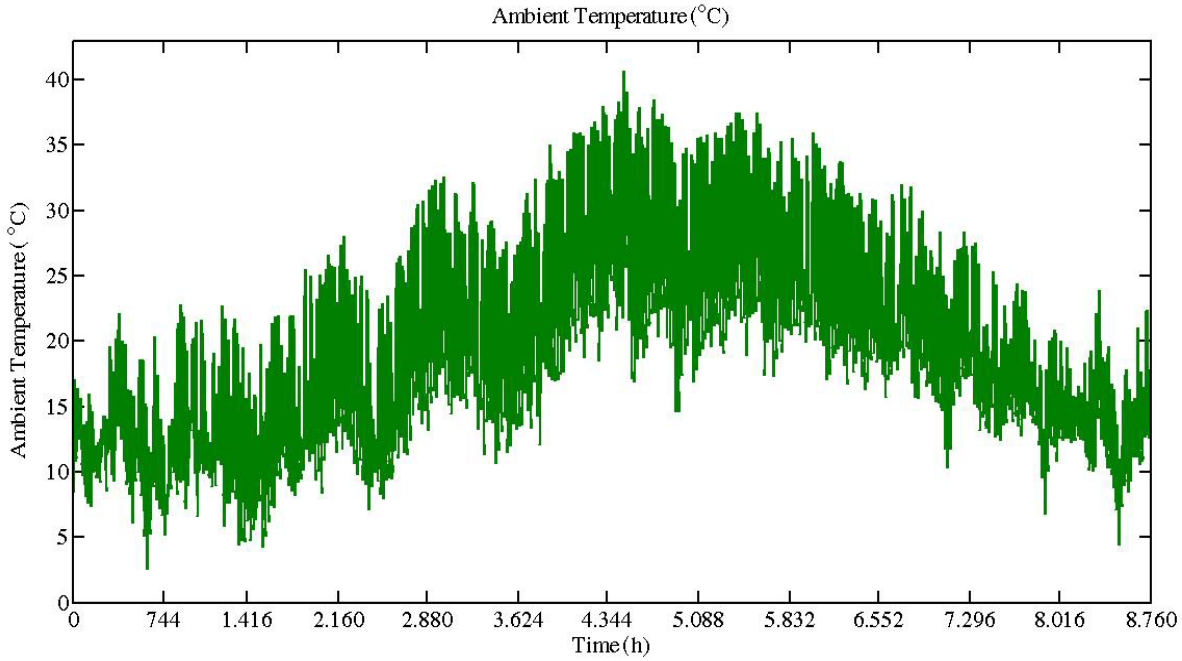


Figure 7-1 Ambient temperature at Rhodos. Hourly data for 1 year.

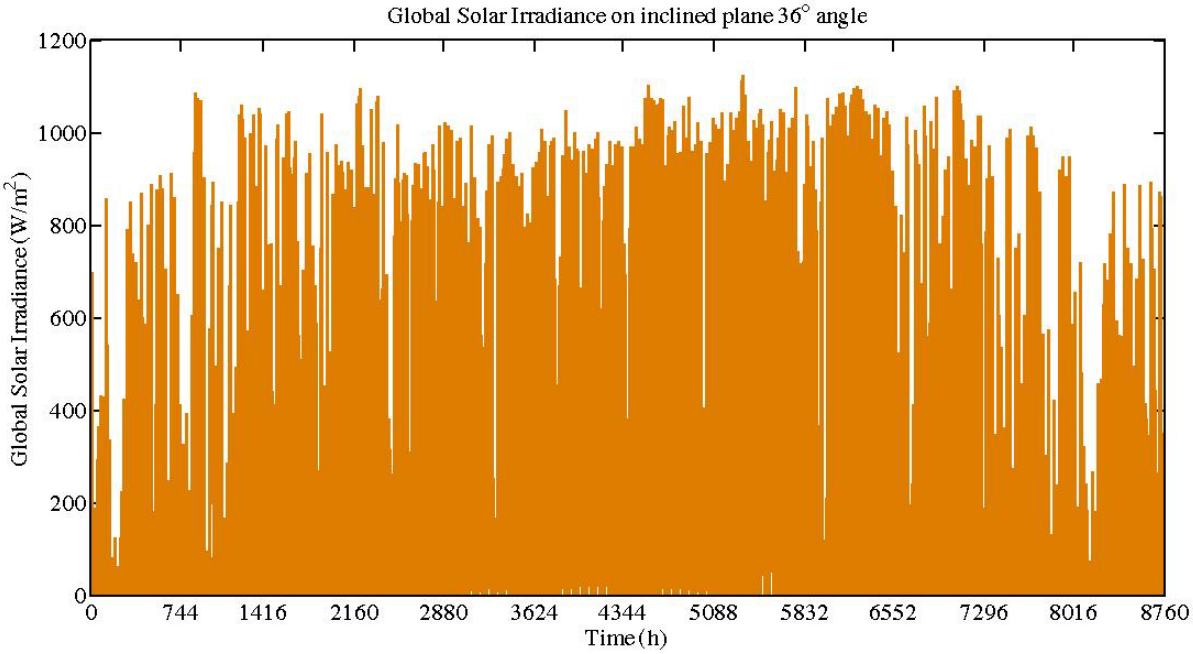


Figure 7-2 Solar irradiance on inclined plane at 36º angle.

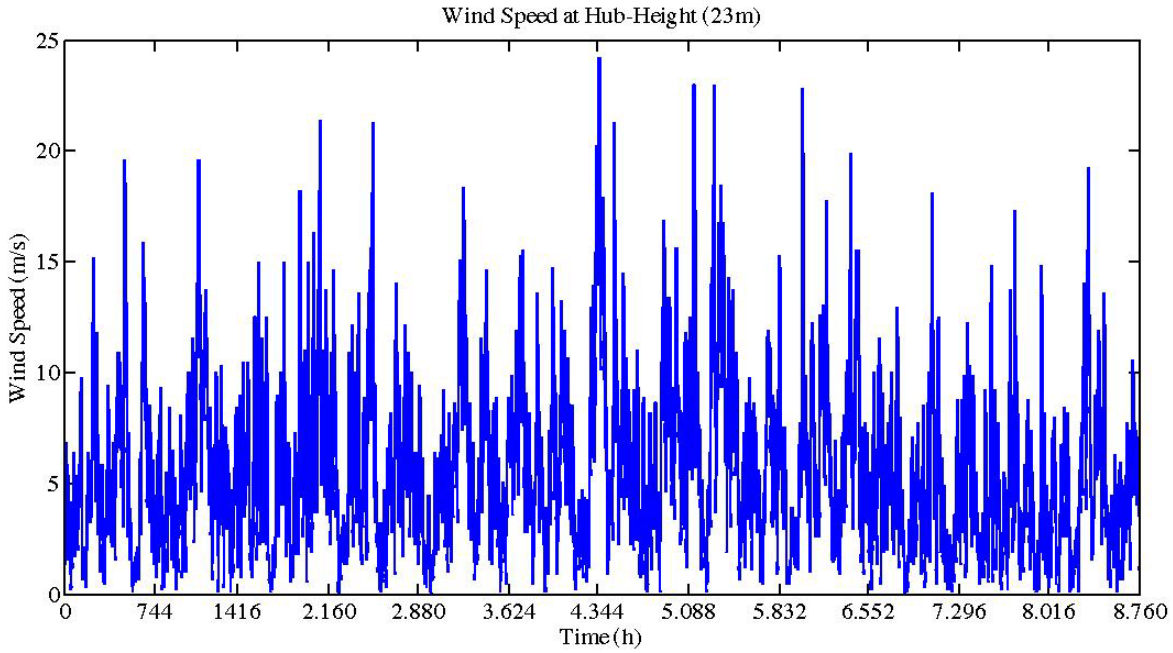


Figure 7-3 Wind speed at hub-height 23m.

Meteonorm is based on databases and algorithms coupled according to a predetermined scheme. For the site of interest data acquisition in the vicinity there is a wmo/omm station, and a space dependent interpolation is done accounting altitude, topography, region etc. and then generating the hourly values by the average monthly values over 10 years.

Weibull probability distribution function of wind speed data at hub-height, 23m, is estimated from eq. (5.1), where *k=1.47607* (*shape factor*) and *c=5.81553* (*scale factor*) and shown at figure 7-4:

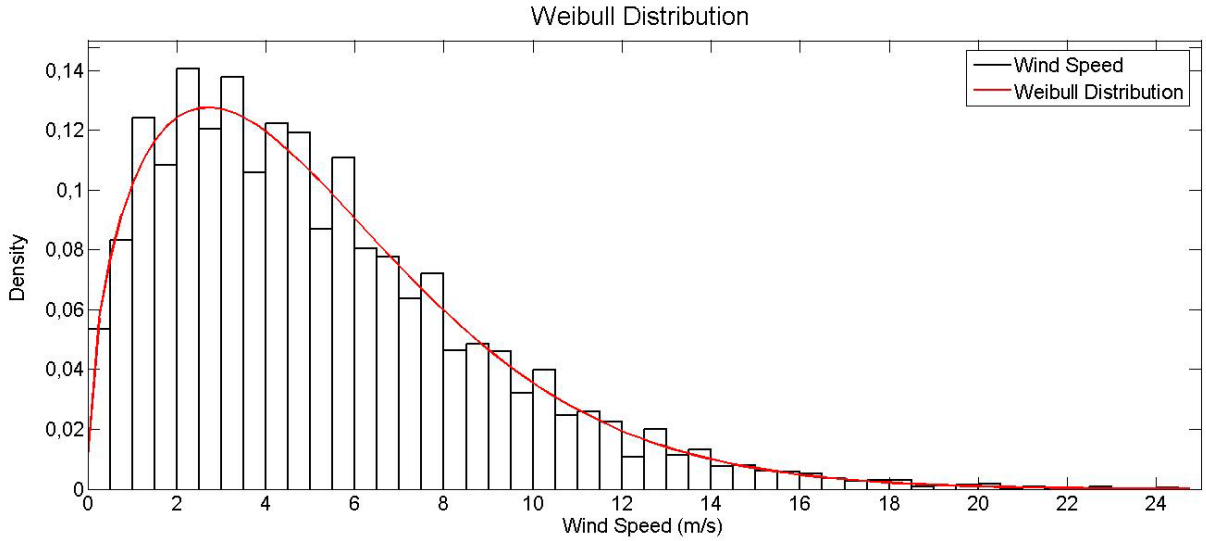


Figure 7-4 Weibull distribution at hub height 23m.

At figure 7-5, is depicted the cumulative frequency of all wind speeds at hub-height of the wind generator.

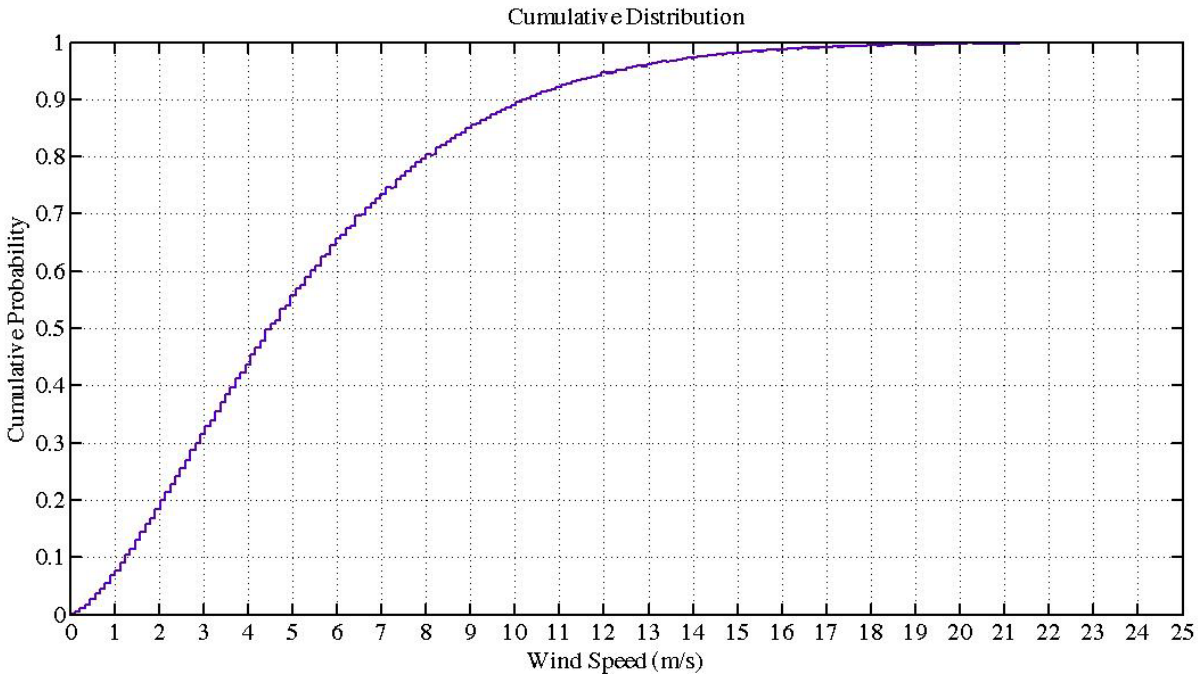


Figure 7-5 Cumulative distribution of wind speed data at hub-height, 23m.

The potential of the energies of solar and wind resources per day and per month on a unit area are given at figure 7-6, translated at 36º angle for the solar energy and 23m height for the wind.

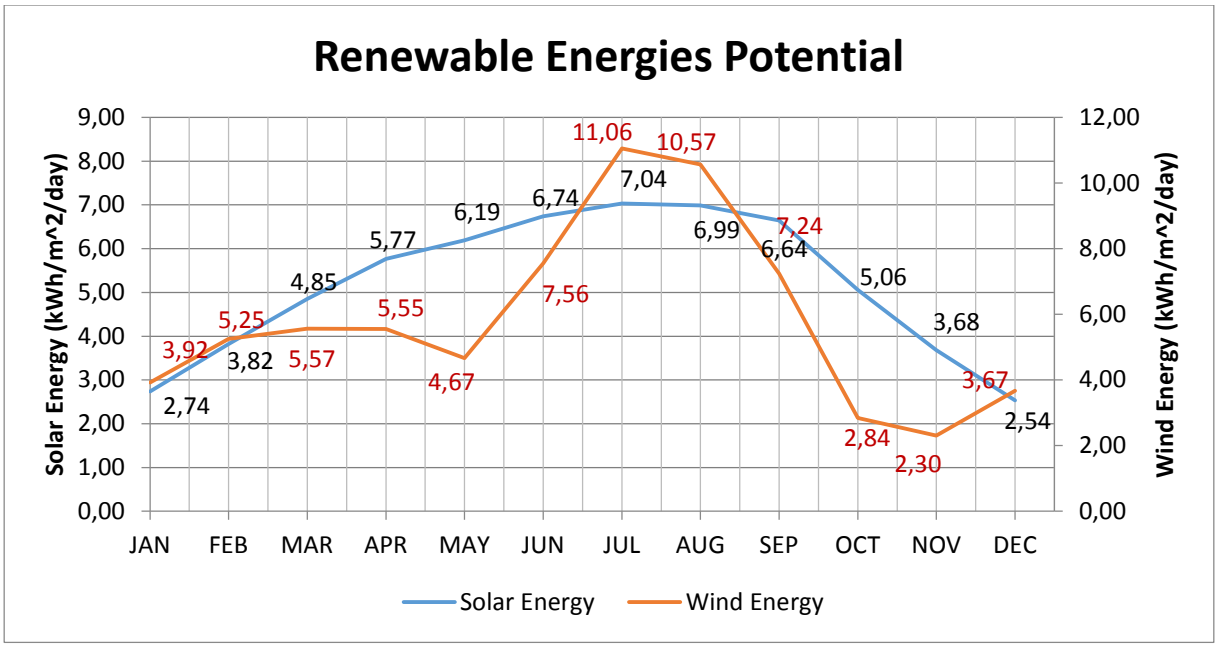


Figure 7-6 Solar and wind energy (kWh) for the site in a unit area per day per month. Solar energy data are for inclined plane 36º and wind data at hub-height 23m.

7.2 LOAD CONSUMPTION PROFILE

One of the most crucial works in renewable energy systems sizing is to record the behavior and needs of the occupants. Some parameters that affect the consumption of electricity are the number of occupants, age, employment status, number of appliances, size and orientation of the house and others. Of the same graveness are both the daily energy consumption and the daily distribution of the consumed energy.

A profile that appears with time lags between generation and consumption will probably require more battery capacity, and if high load peaks occurs then a greater generator might be selected. So all of them interact each other, as for example higher capacity of the batteries it will most likely affect the size of the generator and vice versa.

The adaptation of three different load profiles is studied here and the examination of the effects on system sizing will be considered under two different configurations. Objective of this sub-section is to reveal the necessity for an engineer to study the energy behavior of the occupants and contribute to improve it, and resulting at a system with power reliability and economic effectiveness.

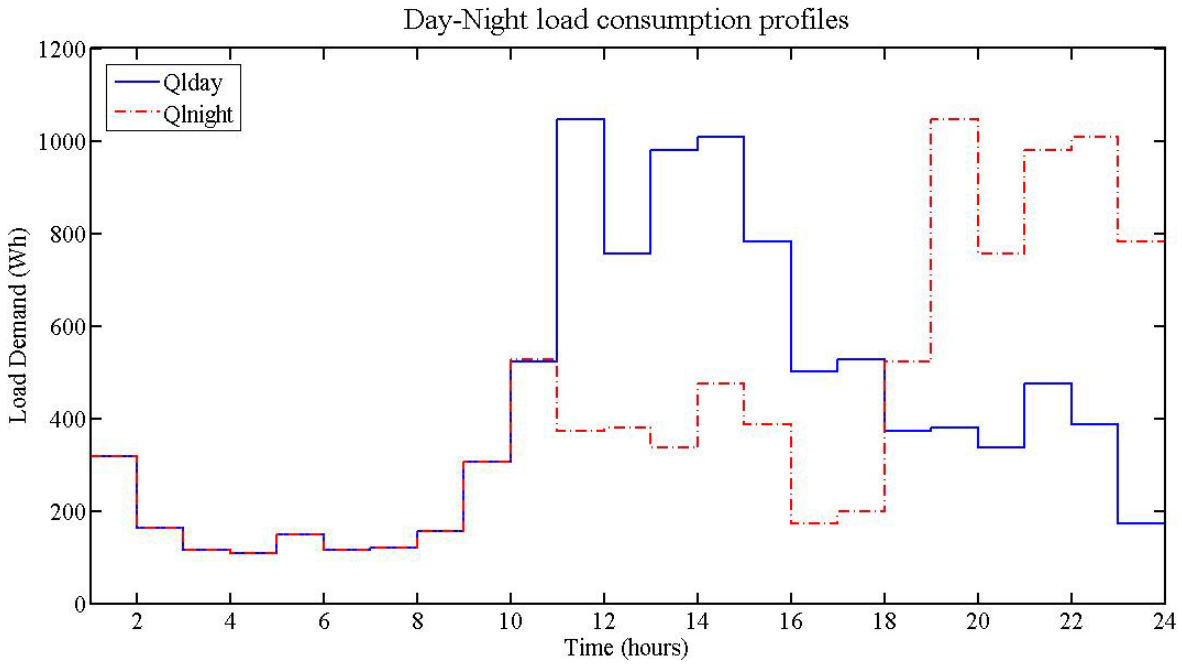


Figure 7-7: Day and night hourly load profiles (10kWh/24h).

At the above figure 7-7 are presented the load profiles that take place in this work. Obviously, for the case of day profile (blue line) the higher values occur at the range of 10:00 to 16:00 with two peaks at 11:00-12:00 and 13:00-15:00. Similarly, at the night profile (red dashed line) we observe that peak hours are shifted at 19:00-20:00 and 21:00-23:00. A comparison about the effects of these

profiles is introduced in this study. Both profiles give a steady daily consumption of 10kWh.

The last profile that is implemented is the hourly-based weekly load profile (figure 7-8). Every day of the week differentiates from the rest, and each one demands the same amount of energy if summed, 10kWh.

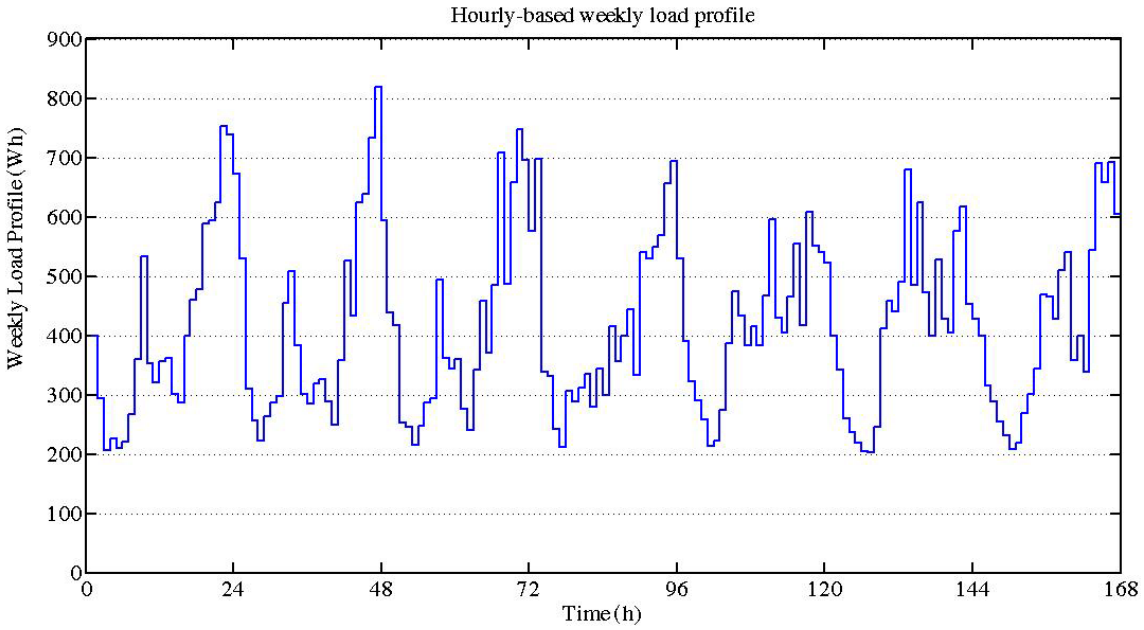


Figure 7-8 Hourly-based weekly load profile (10kWh/day).

7.3 SYSTEM COMPONENTS AND CONFIGURATIONS

In this work, two different configurations will be implemented to satisfy the loads demand of three different load profiles. In the first case both PV and wind generator are provide energy to the batteries via the DC/DC converter and AC/DC, respectively, or directly to the loads with a DC/AC inverter (figure 7-9). For the second configuration wind turbine is directly to the loads via an uninterruptible power supply (UPS), in order to stabilize the power output or the WT and thus protect the devices from unwanted power fluctuations. The surplus energy is stored to the batteries, after the appropriate transformation into DC current via the AC/DC converter (figure 7-10).

The conveyance of the generated energy to the loads or to the storage device appears with lower or higher values depending on the root. Critical for that are the power losses occur from part that justifies the need of greater energy production to that being asked for. Firstly, the two generators are presented with their own efficiencies, namely for the polycrystalline PV modules equals to 0.14 in general but differentiates with ambient temperature and modules technical specifications and for the chosen wind turbine this is accomplished by introducing the polynomial equations from the “fitting” power curve which depend on the wind

speed. Converters efficiencies are also considered, for the two of them AC/DC (n_{acd}) and DC/DC (n_{dcd}). Inverter efficiency nowadays reaches the remarkable rate of 0.9 and taken up constant for this work. Batteries efficiency separated in two conditions; charging process efficiency (n_{cha}) which is taken 0.92 and discharging process (n_{dcha}) equals to 1. As for UPS the efficiency is taken 0.90.

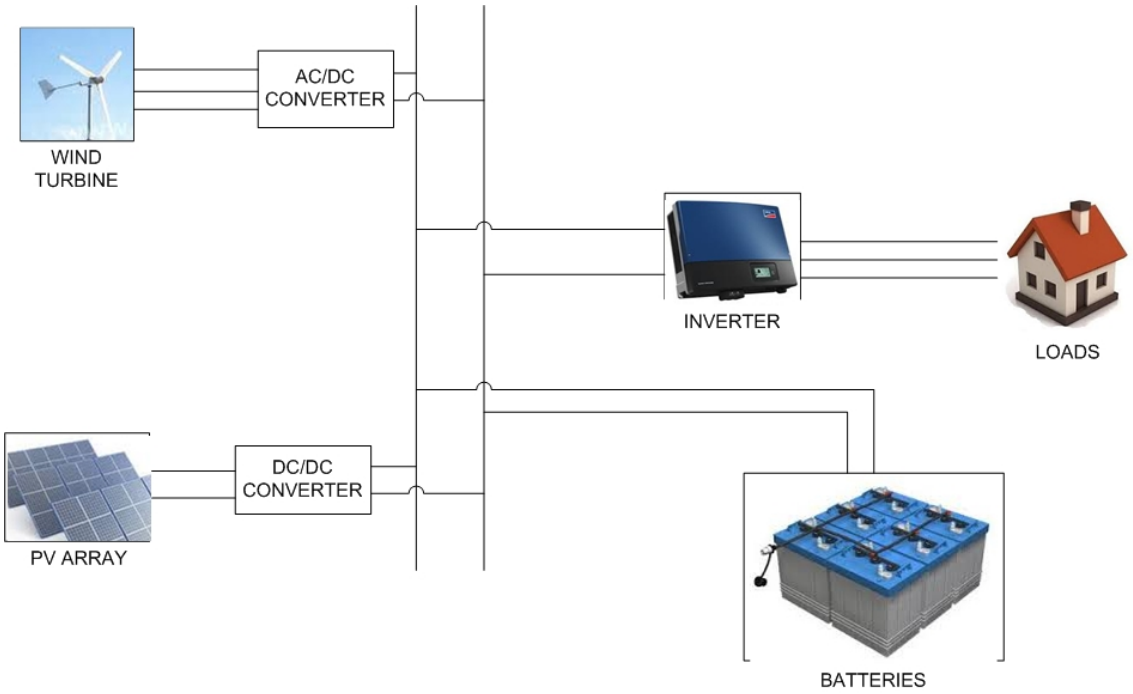


Figure 7-9 Configuration of an autonomous PV/Wind with batteries bank system without UPS

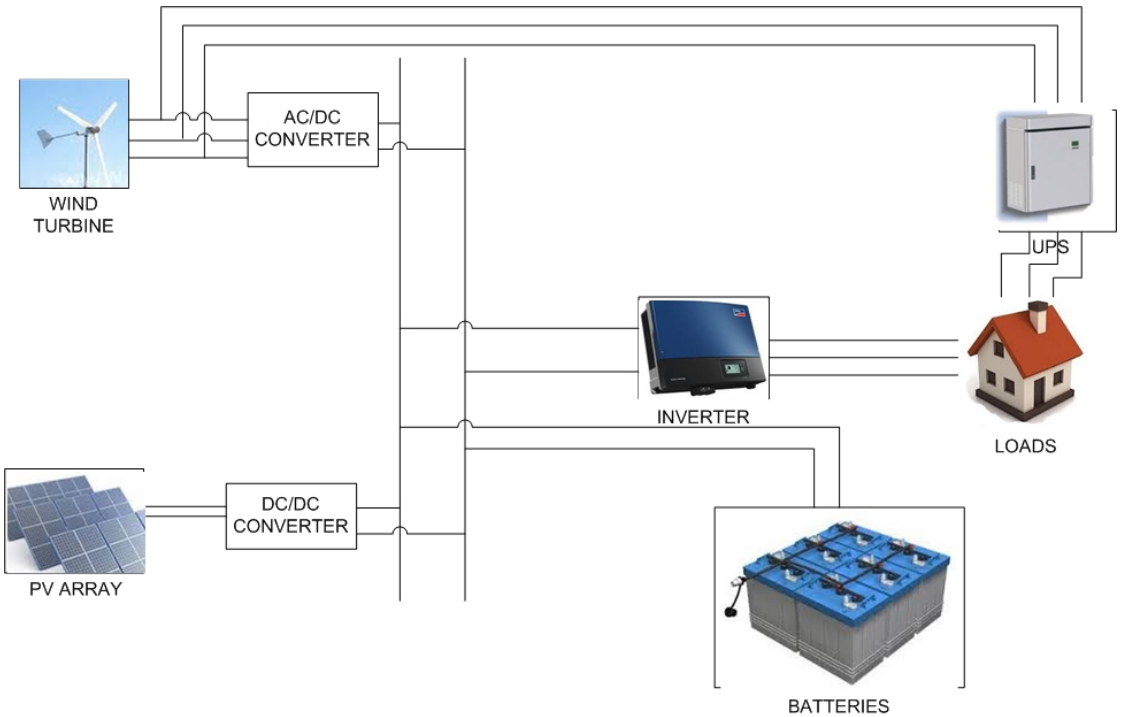


Figure 7-10 Configuration of a stand-alone PV/Wind with batteries banks system with UPS

The methodology that is used in this part calculates the optimal sizing of a PV/wind with batteries systems. Constraints of power reliability and economic effectiveness of the system, namely LPSP and LCE respectively, are used to produce a viable or even profitable solution. Mathematical models for the sizing of the parts of the systems will be presented and also graphic illustration of the results.

8 ANALYSIS OF THE METHODOLOGIES FOR THE ESTIMATIONS OF HYBRID PV-WIND SYSTEMS

This study suggests an optimum hybrid PV-wind with battery banks system that should be installed at a remote site in Rhodos island. The geographic coordinates of the site are latitude 36.24 and longitude 28.05. Meteorological data for global solar radiation, ambient temperature and wind speed were derived from the well-known database Meteonorm[18] in hourly intervals. The angle of the PV-panels is fixed at 36º, as it is theoretically the best inclination for the maximization of the yield of the PV generator and the hub height of the wind generator is 23m.

8.1 METHODOLOGY FOR THE ESTIMATION OF SOLAR RADIATION ON TILTED PLANE

Solar irradiance is calculated on the inclined plane of the PVs in order to estimate their energy output. The steps of this procedure are described here.

8.1.1 Solar declination angle

Declination angle (δ) describes the angle between the equatorial plane and the notional line which joins the center of the sun with earths. It is given by Cooper's [120] formula:

$$\delta = 23.45° \sin\left[\frac{n_j + 284}{365} * 360^o\right] \quad (8.1)$$

Where,

δ = declination angle (degrees)

n_j = the day number, such that n_j = 1 is on the 1st January and 365 on December 31st.

8.1.2 Sunrise equation

The hourly angular displacement of the sun from east to west of the local meridian due to the rotation of the earth around its axis, is 15º per hour, and takes negative values in the morning (east) and positive on the afternoon (west), and is

[18] www.meteonorm.com

called hour angle ω. Next is presented the equation that describes the movement of the sun:

$$\omega = (Solar\ Time - 12) \cdot \frac{15^o}{h} \tag{8.2}$$

Additionally they are determined the sunrise and sunset hours for the specific site's latitude φ, and for the exact declination angle δ of each day n_j. These are exported by the following equation:

$$\omega_s = \cos^{-1}[\cos(-\tan\varphi \cdot \tan\delta)] \tag{8.3}$$

Where,

ω_s: is the hour angle expressed in degrees (ω_{sr}: sunrise angle and ω_{ss}: sunset angle, $-180^o < \omega_{sr} < 0^o$ and $0^o < \omega_{ss} < 180^o$).

For the inclined plane with inclination angle β the sunrise/set hours are estimated by the following equation:

$$\omega_s' = min[\omega_s, \cos^{-1}[\cos(-\tan(\varphi - \beta) \cdot \tan\delta)]] \tag{8.4}$$

8.1.3 Determination of global solar irradiance on inclined plane I_T

For the procedure of estimation of global solar radiation on inclined surface it is necessary to calculate the clearness index, k_t, which is defined as the attenuation factor of the atmosphere and is the fraction of the hourly solar radiation on horizontal surface to the corresponding irradiance available out of atmosphere (I_{ext}). Clearness index is expressed by eq. (8.5):

$$k_t = \frac{I}{I_{ext}} \tag{8.5}$$

The values for global solar radiation I (kw/m^2) and the extraterrestrial irradiance (I_{ext}) are obtained by the meteorological database Meteonorm. The irradiance at the top of atmosphere in hourly intervals is estimated by the following eq. (8.6):

$$I_{ext} = I_{sc} \cdot \left(1 + 0.033 \cdot \cos\left(\frac{360 \cdot n_j}{365}\right)\right) \cdot [\cos\varphi \cdot \cos\delta \cdot \cos\omega + \sin\varphi \cdot \sin\delta] \tag{8.6}$$

Where the solar constant density I_{sc} equals to 1.367 kW/m^2.

After it is estimated the fraction of diffuse radiation to global radiation, as a function of clearness index k_t as defined by Orgill and Hollands [121] and presented under:

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.249 \cdot k_t & k_t < 0.35 \\ 1.557 - 1.84 \cdot k_t & \text{for } 0.35 \le k_t < 0.75 \\ 0.177 & k_t \ge 0.75 \end{cases} \quad (8.7)$$

Beam flux coefficient R_b is determined here, representing the normal beam irradiance that incidents on inclined plane to the normal beam irradiance on horizontal plane:

$$R_b = \frac{I_{bn}}{I_b} \quad (8.8)$$

At eq. (8.8) I_{bn} is the intensity of the solar beam radiation on inclined and I_b on horizontal surface respectively. It can also be expressed as a function of the quotient of the cosines of the incident angle, θ, to zenith angle, θ_z, as shown at next equation:

$$R_b = \frac{I_{bd} \cdot \cos\theta}{I_{bd} \cdot \cos\theta_z} = \frac{\cos\theta}{\cos\theta_z} \quad (8.9)$$

The incident angle θ varies from 0° for normal to the surface sunrays and 90° for parallel sunrays. Angle θ_z expresses the angle among conceivable zenith line and the conceivable line of the sun disc center to the surface. For the estimation of cosine θ, the following eq. (8.10) is used:

$$\begin{aligned} \cos\theta = {} & \cos\beta \cdot \sin\delta \cdot \sin\varphi - \cos\varphi \cdot \sin\delta \\ & \cdot \cos\gamma \cdot \sin\beta + \cos\beta \cdot \cos\varphi \cdot \cos\delta \\ & \cdot \cos\omega + \cos\delta \cdot \cos\gamma \cdot \sin\varphi \cdot \sin\beta \\ & \cdot \cos\omega + \sin\gamma \cdot \sin\beta \cdot \cos\delta \cdot \sin\omega \end{aligned} \quad (8.10)$$

Where β is the inclination angle of the plane, γ is the surface azimuth angle and φ is the latitude of the location. And if we assume that inclination angle, β, and azimuth angle, γ, are equal to 0 then from the previous equation of $cos\theta$ we get eq. (8.11) of $cos\theta_z$:

$$\cos\theta_Z = \cos\delta \cdot \cos\varphi \cdot \cos\omega + \sin\delta \cdot \sin\varphi \quad (8.11)$$

Thus, from equations (8.10) and (8.11) it is estimated the beam flux coefficient R_b from eq. (8.9).

Next, the estimation of the improved coefficient R for the intensity of the global solar radiation from horizontal on inclined plane is conducted using the expression first introduced by Liu and Jordan [122]:

$$R = \frac{I_b}{I} \cdot R_b + \frac{I_d}{I} \cdot \left(\frac{1 + cos\beta}{2}\right) + \left(\frac{1 - cos\beta}{2}\right) \cdot r$$
$$= \left(1 - \frac{I_d}{I}\right) \cdot R_b + \frac{I_d}{I} \cdot \left(\frac{1 + cos\beta}{2}\right) \quad (8.12)$$
$$+ \left(\frac{1 - cos\beta}{2}\right) \cdot r$$

Where the fraction $\frac{I_d}{I}$ is calculated from eq. (8.7) and depends on clearness index *kt* and *r* represents the albedo, which is the reflectance coefficient of the ground generally for most surfaces equals to 0.2.

Finally, it is estimated the hourly solar radiation that hits on the inclined surface of the PVs using the general expression for conversion coefficient *R* which is defined as the quotient of global solar radiation on inclined to horizontal plane as shown under:

$$R = \frac{I_T}{I} => I_T = R \cdot I \quad (8.13)$$

where the global solar irradiance, *I*, is derived from Meteonorm on hourly intervals.

8.2 ITERATIVE AND GRAPHICAL SIZING APPROACHES

In this study different sizing approaches of a hybrid PV-wind system will be investigated and compared in terms of feasible system acquisition and economic features. The two methodologies are a graphical construction approach introduced by Tomas Markvart [50] and the proposed analytical dynamic iterative simulation technique and the results will be thoroughly discussed.

8.2.1 Graphical construction approach

Tomas Markvart's aim was to produce a system that could take advantage of the two energy sources in order to provide a more reliable system with the least possible generators. They are used the monthly averaged values of the mean daily monthly solar irradiance and wind speeds and assumed that the statistical variations of energy supply from the average values were theoretically taken up by batteries, without estimating the appropriate capacity. The differentiation of this approach is that examines the seasonally variation and doesn't accounts the hourly variations. The load that was determined to supply equals to 10kWh per day and is constant during all the days of the year.

Thus, summarizing all the previous a hybrid system will be calculated that generates the proper power to satisfy the loads that supposed to be flat at 10kWh per day, for the site of interest in our case which is Rhodos. Hence, the generator will be sized for the minimum of the corresponding energy supply, and for the rest of the year the surplus energy delivered by the system will be wasted. The steps for these calculations are shown under.

8.2.1.1 Daily Energy Balance

Several definitions will be presented here to better understand the following procedure. Firstly, the sizes of the generators are given as the product of the efficiency to the effective area. So, the PV array is calculated by the equation (8.14):

$$a_H = n \cdot A \text{=} 0.14/\text{m}^2 \tag{8.14}$$

where $n = 0.14$ is module's efficiency and A is the PV array area. The estimated power equals to the peak power rating of the array in kWp per unit area (m^2). Similarly for the wind turbine we get equation (8.15):

$$a_w = C_p \cdot (\pi \cdot r^2) \text{=} 2.36/\text{WT} \tag{8.15}$$

where $C_p = 0.48$ is the power coefficient of WT, and $r = 1.25m$ is the radius of the rotor. For an incident power density of the wind being 1kW/m^2 the size of the WT is identical to equation (8.15) in kW. These two equalities provide a conveniently symmetric description of the generators.

The delivered energy to the loads is produced by the solar intensity that incidents on PV per unit area. As for the solar irradiance it is used the daily average value acquired from the database (Meteonorm) and transposed to the inclined plane at 36°. The wind is measured on a plane perpendicular to the wind direction, and is given by the following equation (8.16), per unit area (m^2):

$$W = \frac{D}{2} \cdot \rho_{air} \cdot \langle v^3 \rangle \tag{8.16}$$

where ρ_{air}=1.17 kg/m^3 is the air density at 25°C, and v is the daily monthly average wind velocity for the duration D of 1 day (24hours). Assuming the daily average demand as a function of time for all months of the year under consideration, then we can write down the set of conditions (8.17) that should be accomplished to satisfy the load for each month separately, for a steady load of 10kWh per day for all months:

$$\begin{cases} Q_{L-Jan} \leq W_{Jan} \cdot a_w + H_{T\_Jan} \cdot a_H \\ Q_{L-Feb} \leq W_{Feb} \cdot a_w + H_{T\_Feb} \cdot a_H \\ \dots \\ Q_{L-Dec} \leq W_{Dec} \cdot a_w + H_{T\_Dec} \cdot a_H \end{cases} \quad (8.17)$$

The subject of this approach is to provide the range of the sizes of the generators a_H, a_w that must obey to the principal that the energy produced by the system should be greater or equal to the load demand. In the search for optimum only the boundary conditions are appropriate which provide three possible alternatives of PV, wind turbine and hybrid system each one corresponding to a vertex on the boundary.

8.2.1.2 Graphical Formalism of Seasonal Analysis

In this part a Cartesian plane of the variables a_H and a_w is defined where each point represents a specific configuration and its' coordinates provide us the size of each generator. The obtained solutions are infinite and therefore the introduction of a constraint which reduces the possible configurations to those that considered to be optimal is necessary. Markvart considers the cost of the system and sets the condition for the minimization as follows (8.18):

$$Hybrid\ Generator\ Cost = c_H \cdot \alpha_H + c_w \cdot \alpha_w \quad (8.18)$$

where c_H and c_w are the costs of the PV and wind generators per unit power of the output rating respectively. Then subject to conditions (8.17) and (8.18) and by the use of linear programming theory we can obtain a cost effective system. A Cartesian plane is created with coordinates the sizes of the generators (aH,aw) and the intersection points of the plotted lines which represent the months of the yeear denotes a hybrid system. From the resulted lines of supply-demand condition the locus of the intersection between them is defined at times t and (t+δt) by the following system of equations:

$$\begin{cases} Q_L(t) = H_T(t) \cdot a_H + W(t) \cdot a_w \\ Q_L(t+\delta t) = H_T(t+\delta t) \cdot a_H + W(t+\delta t) \cdot a_w \end{cases} \quad (8.19)$$

The set of equations (8.19) for $\delta t \rightarrow 0$ then become:

$$\begin{cases} a_H(t) = \dfrac{Q_L(t) \cdot W'(t) - Q_L' \cdot W(t)}{H_T(t) \cdot W'(t) - H_T' \cdot W(t)} \\ a_w(t) = \dfrac{Q_L(t) \cdot H_T'(t) - Q_L' \cdot H_T(t)}{W(t) \cdot H_T'(t) - W'(t) \cdot H_T(t)} \end{cases} \quad (8.20)$$

Where prime indicates the derivative with respect to time (t). By solving the system of eqs. (8.20) we get the intersection of the lines which are the boundary solutions and represent the possible hybrids for the system.

8.2.2 Iterative approach

Aim of this study is to produce an algorithm for the sizing of a renewable power generation system that exploits solar and wind energies, and storages the excess energy at battery banks. Two types of configurations will be firstly evaluated with technical criteria, then optimized under economic criteria and compared. Next, a comparison between two different power evaluation criteria, namely Loss of Power Supply Probability (LPSP) and Loss of Load Probability (LLP) will be presented. Also, the behavior of the system for different load profiles will be carried out and the system specifications will be thoroughly assessed.

In the design stage, the system's configuration is synthesized, i.e. which types of generation technologies will be allocated and integrated to build a hybrid system. This is very crucial aspect in the design, since there are usually many alternative possibilities related to which individual components will be included in a hybrid energy system [stand-alone and hybrid wind].

The followed method to estimate our system is an iterative programming technique with matlab software. Configurations are shown at figure 7-9 and figure 7-10. Principal subsystems that take part on the configuration and being modelled are the two generators of the PV and wind, and the battery storage devices. Below are described the relations for each one. All other parts appeared with a constant efficiency factor and no modelling is provided, although they influenced by different factors.

8.2.2.1 PV generator modelling

For the PV modules we used the solar irradiation on tilted plane as calculated in previous section. Other important data being imported are the ambient temperature, derived by Meteonorm at hourly increments, and manufacturer data for the module. The power output then is given by (Markvart 2000):

$$P_{PV} = N \cdot A_{PV} \cdot I_T \cdot n_{PV}$$

where n_{PV}, is the instantaneous PV generator efficiency consists of polycrystalline modules, A_{PV} is the area of the module considered per unit of 1m^2, I_T the solar irradiance on inclined plane (W/m^2), and last *N* is the number of the modules.

The instantaneous efficiency of the module is further estimated by the use of equation (8.21):

$$n_{PV} = n_r \cdot n_{pt} \cdot [1 - \beta_t \cdot (T_c - T_r)] \tag{8.21}$$

where n_r=0.14 is the reference efficiency of polycrystalline PV module, n_{pt}=1 is the power conditioning efficiency with a perfect power point tracker, β_t=0.005/^{o}C PV's efficiency temperature coefficient, T_c (^oC) is the cells temperature by eq. (8.22), $T_r = 25\ ^oC$ is the reference cell temperature.

$$T_c = T_a + I_t \cdot \left(\frac{NOCT - 20}{800}\right) \tag{8.22}$$

where $NOCT = 47\ ^oC$ is the nominal operating cell temperature.

8.2.2.2 Wind turbine modelling

A horizontal axis wind turbine (HWAT) is chosen with a rated power output of 500W. The manufacturer of the turbine is HUMMER. From the data provided by the manufacturer it was created a polynomial set of equations with interpolation, and quite smooth cubic splines were created as seen in figure 8-1 [108]. The fitting set of equations for the characteristic output of the generator is given by (8.23):

$$P_{WG}(v) = \begin{cases} 0 & v \le v_{cut-in} = 3\ or\ v \ge v_{cutout} = 20 \\ 1.333v^3 + 3.5v^2 - 9.833v - 4 & 3m/sec < v \le 6m/sec \\ -1v^3 + 22.29v^2 - 15.57v - 142.1 & 6m/sec < v \le 10m/sec \\ 12v^3 - 145.5v^2 + 5457v - 2.109 \cdot 10^4 & 10m/sec < v \le 13m/sec \\ -0.833v^3 + 35v^2 - 553.2v + 4035 & 13m/sec < v \le 16m/sec \\ -0.833v^3 + 48v^2 - 974.2v + 7443 & 16m/sec \le v \le 20m/sec \end{cases} \tag{8.23}$$

where $P_{WG}(v)$ is the power output of the turbine at different wind speeds.

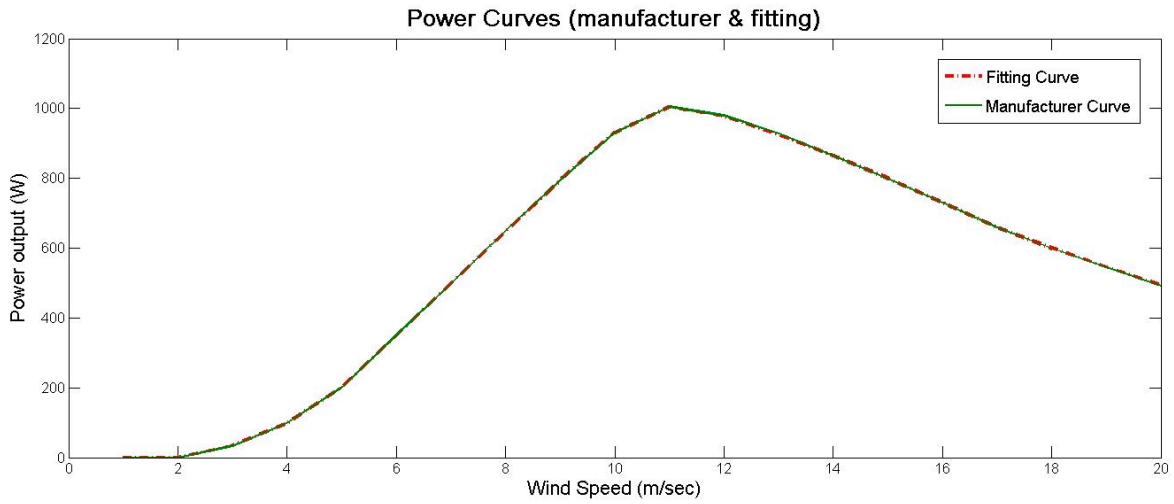


Figure 8-1 The power curve of the wind turbine produced from the cubic polynomial equations appears to be identical with the one provided from manufacturer's data.

The height adjustment of the wind data derived to the installation height of the hub was calculated by applying the power of law eq. (5.2):

$$v = v_r \cdot \left(\frac{h}{h_r}\right)^n$$

where, v and v_r represent the wind speed at hub height $h=23m$ and at reference height $h_r=10m$, and $n=1/7$ is the power law exponent for low roughness surface [105].

8.2.2.3 Batteries modelling

Batteries store the excess energy produced by the generators at any hour. At opposite, batteries are discharging when deficit in energy produced occurs. For the case that the stored energy is depleted simultaneously with insufficient energy production, a failure to satisfy the loads appears. Thus, the decision for charging or discharging the batteries is defined on the excess or deficit energy produced and for the second case the state of battery charge.

In charging phase, the available capacity of the batteries for time t depends on the type of configuration. In the first configuration this is prescribed by eq. (8.24):

Figure 7-9

$$C_{bat}(t) = C_{bat}(t-1) \cdot (1-\sigma) + \left(P_{PV}(t) \cdot n_{dcd} + P_{WG}(t) \cdot n_{acd} - \frac{P_{LD}(t)}{n_{inv}}\right) \cdot n_{bat-cha} \cdot \Delta t \quad (8.24)$$

For the second type of system where wind turbine is taken as a primary source the capacity of the batteries is detached in two cases depending on the inequality between the power output of the wind turbine and loads demand. When $P_{WG}(t) \geq P_{LD}(t)$ then eq. (8.25) provides the energy delivered to the batteries, else if $P_{WG}(t) < P_{LD}(t)$ this is given by eq. (8.26).

Figure 7-10

$$P_{WG}(t) \geq \frac{P_{LD}(t)}{n_{UPS}} \qquad \begin{aligned} C_{bat}(t) = C_{bat}(t-1) \cdot (1-\sigma) \\ + \big(P_{PV}(t) \cdot n_{dcd} \\ + (P_{WG}(t) - P_{LD}(t)) \cdot n_{acd}\big) \\ \cdot n_{bat-cha} \cdot \Delta t \end{aligned} \tag{8.25}$$

$$P_{WG}(t) < \frac{P_{LD}(t)}{n_{UPS}} \qquad \begin{aligned} C_{bat}(t) = C_{bat}(t-1) \cdot (1-\sigma) \\ + \left(P_{PV}(t) \cdot n_{dcd} \right. \\ \left. - \left(\frac{P_{LD}(t) - P_{WG}(t)}{n_{inv}} \right) \right) \cdot n_{bat-cha} \cdot \Delta t \end{aligned} \tag{8.26}$$

At the above eqs. (8.25) & (8.26) of batteries charging state $C_{bat}(t)$ and $C_{bat}(t-1)$ represent the stored energy at the batteries (Wh) for times t and (t-1), respectively, $P_{LD}(t)$ is the power asked by the loads at time t, Δt is the following time step (Δt=1hr), n_{acd} is AC/DC convertors efficiency and n_{dcd} is DC/DC convertors efficiency, $n_{bat-cha}$ is the efficiency for batteries charging taken equal to 0.92, n_{inv} is the efficiency of the inverter that transforms the current from DC to AC, taken 0.90, and σ is the self-discharging rate of the batteries, 3% monthly.

When the loads demand more power than the produced by the system then batteries are forced to provide the extra power with the restriction of minimum available capacity. This least possible state is determined by the maximum permissible depth of discharge.

$$C_{bat-min} \leq C_{bat}(t) \leq C_{bat-max} \tag{8.27}$$

$$C_{bat-min} = DOD \cdot C_{bat-n} \tag{8.28}$$

At eq. C_{bat-n} is the nominal capacity of the battery (Wh) given by the manufacturer. Here, is assumed to be 1000Wh.

The conditions for the discharging state are calculated by eqs. (8.29) & (8.30), considering the configuration design for figure 7-9 & figure 7-10, in that order.

Figure 7-9

$$C_{bat}(t) = C_{bat}(t-1)\cdot(1-\sigma) + \left(\frac{P_{PV}(t)\cdot n_{dcd} + P_{WG}(t)\cdot n_{acd} - \frac{P_{LD}(t)}{n_{inv}}}{n_{bat-discha}}\right)\cdot \Delta t \quad (8.29)$$

Figure 7-10

$$C_{bat}(t) = C_{bat}(t-1)\cdot(1-\sigma) + \frac{1}{n_{bat-discha}}\left(P_{PV}(t)\cdot n_{dcd} - \left(\frac{P_{LD}(t) - P_{WG}(t)}{n_{inv}}\right)\right)\cdot \Delta t \quad (8.30)$$

where $n_{bat-discha}$ is the battery discharging efficiency, equal to the unit.

Next, it is evaluated the reliability of the stand-alone HPWS with the technical constraint of LPSP and LLP, and then is economical optimized under the criteria of LCE. The methodologies are being followed are described here.

8.2.2.4 Technical evaluation with LPSP/LLP

Examination of the power reliability of the system is of vital importance and the analysis is very important in the designing phase. Loss of power supply probability is used here and the system is sized with three different values, namely 0%, 5% and 10%.

The definition of LPSP is the ratio of energy deficit to the total demand by the loads during the period of a typical year in hourly increments (*T=8760hr*) and given by eq. (3.1):

$$LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_{LD}(t)\cdot \Delta t}$$

In the instance that the battery capacity reaches its lowest value and the total generated power falls short from the required, the loss of power occurs then and is expressed by the general formation eq. (8.31):

$$LPS(t) = (P_{LD}(t) - P_{tot}(t))\cdot \Delta t \quad (8.31)$$

where $(P_{tot}(t)\cdot \Delta t)$ is the total energy provided by the system, consisted of the produced amount from the generators and the portion of the stored energy in batteries that can be given to the system, and calculated depending on the configuration type as follows:

Figure 7-9

$$P_{tot}(t) \cdot \Delta t = \Big(\big(P_{PV}(t) + P_{WG}(t)\big) \cdot \Delta t + C_{bat}(t-1) - C_{bat-min}\Big) \cdot n_{inv} \quad (8.32)$$

Figure 7-10

$$P_{tot}(t) \cdot \Delta t = P_{WG}(t) \cdot \Delta t + (P_{PV}(t) \cdot \Delta t + C_{bat}(t-1) - C_{bat-min}) \cdot n_{inv} \quad (8.33)$$

Here, it will also be performed a technical approach with the loss of load probability (LLP) method. LLP provides the failure time of the system against the total operating time of the system, as shown in eq. (3.3).

$$LLP = \frac{T_f}{T}$$

where, T_f is the failure time of the system and T is the total examined period of the system, being 8760hr. For the times t that the system fails to satisfy the loads eq. (3.4), are added up.

$$\sum_{t=1}^{T} (E_{WG}(t) + E_{PV}(t) - E_{LD}(t)) < 0$$

where, E_{WG} is the produced energy of the wind generator, E_{PV} refers to the generated energy of the photovoltaics and E_{LD} is the energy demand at time *t*.

At the opposite case, by means of having batteries charged at maximum and the energy production is beyond the loads demand, the excess energy is then calculated with the help of the following expressions depending on the configuration type:

Figure 7-9

$$WE(t) = \big(P_{PV}(t) + P_{WG}(t)\big) \cdot \Delta t - \left(\frac{P_{LD}(t)}{n_{inv}} \cdot \Delta t + \left(\frac{C_{bat-max} - C_{bat}(t-1)}{n_{cha}}\right)\right) \quad (8.34)$$

Figure 7-10

$P_{WG}(t) \geq P_{LD}(t)$

$$WE(t) = \big(P_{PV}(t) + (P_{WG}(t) - P_{LD}(t))\big) \cdot \Delta t - \left(\frac{C_{bat-max} - C_{bat}(t-1)}{n_{cha}}\right) \quad (8.35)$$

$$P_{WG}(t) < P_{LD}(t) \qquad \begin{aligned} WE(t) = {} & P_{PV}(t) \cdot \Delta t \\ & - \left(\frac{P_{LD}(t) - P_{WG}(t)}{n_{inv}} \cdot \Delta t \right. \\ & \left. + \left(\frac{C_{bat-max} - C_{bat}(t-1)}{n_{cha}} \right) \right) \end{aligned} \tag{8.36}$$

The renewable contribution (RC) over a period T, here is one year, is defined as the difference between the unit and the chosen value of LPSP and it is:

$$RC(T) = 1 - LPSP \tag{8.37}$$

And finally the proportion of the wasted energy for the given period (T) is expressed by the fraction of the wasted energy to the total energy produced:

$$EXC(T) = \frac{WE(T)}{P_{tot} \cdot T} = \frac{WE(T)}{E_{tot}(T)} \tag{8.38}$$

With the objective function produced, a set of configurations that satisfy the system power reliability is obtained. The optimal solution is defined with the LCE criteria.

8.2.2.5 Cost optimization of the system

The concern of many projects is to provide electricity with the lowest energy cost. Therefore, the particular work analyses the cost of the system using the indicator of levelized cost of energy (LCE). This concept provides the optimal system that must be a viable solution, or even more a profitable one.

LCE is defined as the fraction of the total annualized cost (TAC) of the system divided by the annual electricity delivered by the system, and is expressed:

$$LCE = \frac{TAC}{E_{LD}} = \frac{TPV \cdot CRF}{E_{LD}} \tag{8.39}$$

where E_{LD} is the annual total energy in kWh, TPV is the total present value of the actual costs of system components, and CRF represents the capital recovery factor (CRF) given by eq. (3.10):

$$CRF = \frac{r(1+r)^t}{(1+r)^t - 1}$$

where, *r=8%* is the annual discount rate, and *t* is the life span of the energy system under examination (25years). The annual discount rate represents the profits and other benefits of the hybrid's system project, expressed in the portion of the annual performance of the initial costs of the project. The value of *r* gives a net present value equal to zero, and higher values are desirable to undertake the project.

$$TPV = C_{PV} + C_{wind} + C_{bat} \tag{8.40}$$

At eq. (8.40) C_{PV} represents the summary of the present value for all the costs of the PV generator in useful lifetime, including initial capital costs, maintenance costs (C_m), installation and connection costs being close to 35% of the total cost of the PV generator, C_{wind} is the sum of present values of initial capital, maintenance (C_m), installation and connection costs of the wind turbine in systems life, estimated to be 20% of the total cost of the wind turbines, and C_{bat} is the present value of capital and replacement costs (C_R) in system life.

In this study the parts that being replaced during lifetime of the system are batteries, inverter and UPS. For batteries the present value is provided by:

$$C_R = C_{bat-c} \cdot \sum_{i=1}^{N_{rem}} \left(\frac{1+g_1}{1+r}\right)^{T/N_{rem}+1} \tag{8.41}$$

Here, C_{bat-c} is the initial cost of the battery (€), g_1 is the inflation rate of component replacements, N_{rem} is the number of replacements for the components in life span, r is the annual discount rate, and T is the period of life for the system (25 years). The same process is conducted and for the UPS and inverter. The present value of the maintenance costs is expressed then [123]:

$$C_m = C_{m0} \cdot T \tag{8.42}$$

$$C_{m0} = m_{PV} C_{PVA} + m_{WG} C_{WGA} \tag{8.43}$$

Where C_{m0}, is the maintenance cost in the first year, C_{PVA} is the initial cost and m_{PV} is 1% of the initial cost for the PV generator and the inverter, and C_{WGA} is the initial cost and m_{WG} 3% of the initial cost for wind generator. All others components are without maintenance costs.

Finally, is determined the net present value (NPV) for the system to assess the investment, according to the relation:

$$NPV = -CI + \sum_{t=1}^{N} \frac{C_{in}}{(1+r)^t} - \sum_{t=1}^{N} \frac{C_{out}}{(1+r)^t} \tag{8.44}$$

Where, CI is the total purchase and installation costs, C_{in} refers to the load demand satisfied by the system and multiplied with the cost of the public

electricity provider per unit of kWh, 0.22€/kWh, which has an increasing rate close to 3%[19] annually, and C_{out} expresses the maintenance costs for the two generators and the replacement costs of the batteries. The NPV criterion accepts projects that have an NPV greater than zero.

All the costs of the system parts used in this work are presented at table 8-1 and table 8-2.

Table 8-1 Price, maintenance cost per year, lifetime and BOS[20].

Components	Price (€/W)	Maintenance cost per year of price	Lifetime	BOS
PV module	0.76	1%	25	35%
Wind generator	1.25	3%	25	20%
Inverter	0.5	0%	10	-
UPS	0.273	0%	10	-
Battery Bank	0.157	0%	10	-

Table 8-2 Technical and economical data of PV, wind turbine and battery.

Photovoltaic Type	Cost (euro/W)	Cost (euro/m^2)	Efficiency Range (%)	Mean Efficiency (%)	BOS
Poly-crystalline (140W/m^2)	0.76	106,4	12-16	14	40% of cost

Wind Turbine Type	Cost (euro/W)	Cost (euro/WT)	BOS
HUMMER 500W	1.25	625	20% of cost

Battery Discharge Type	Cost (euro/W)	Nominal capacity (Ah)	Voltage (V)	Minimum charge (%)	BOS
Deep – AGM	0.157	83,33	12	20	0% of cost

8.2.3 Analysis of the algorithm (Flowchart)

Scope of this section is to fully analyze the procedure of the implemented analytic dynamic iterative algorithm that developed in this project for the appropriate estimations of the hybrid energy system constituted of PV-wind generators and batteries as a storage bank.

Firstly, it is established the algorithm for the configuration shown at figure 7-9 at which both generators well thought-out as primary and two different power criteria of LLP and LPSP are used.

[19] http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Energy_price_statistics

[20] BOS is the balance of system and is constituted of the costs for installation and connection.

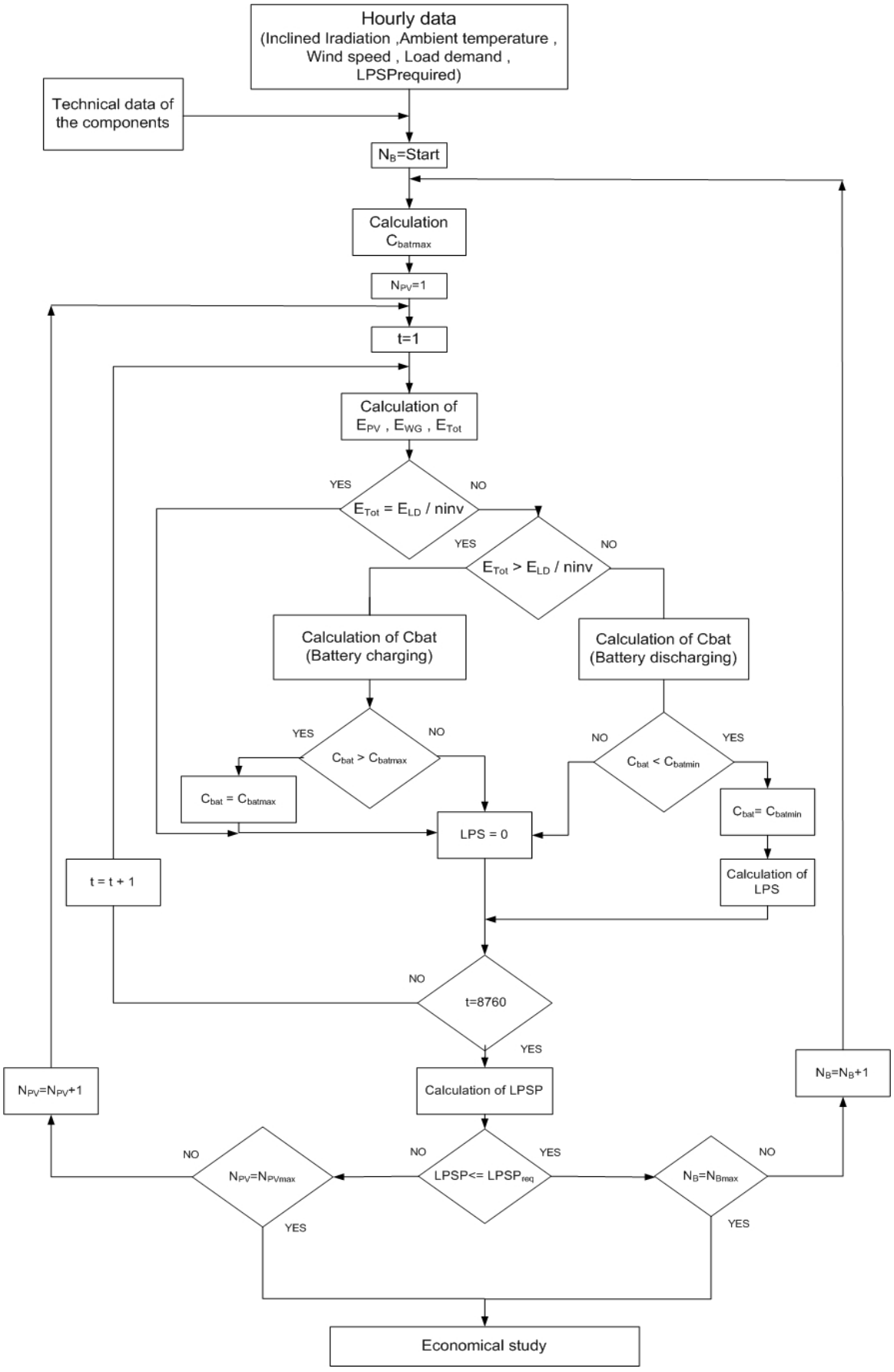


Figure 8-2 Flowchart for the sizing of the hybrid system without UPS and with LPSP power evaluation criterion.

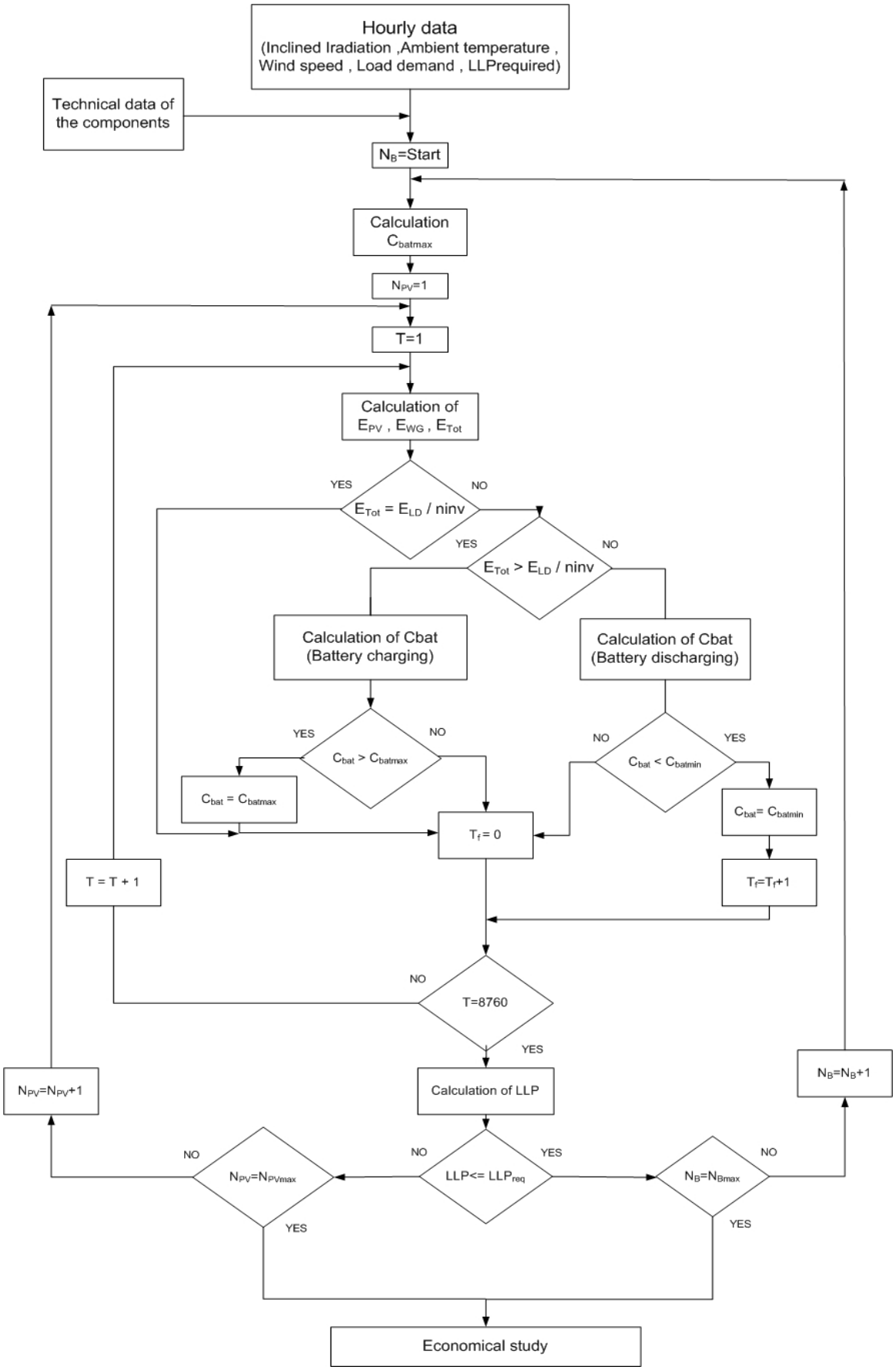


Figure 8-3 Flowchart for the sizing of the hybrid system without UPS and with LLP power evaluation criterion.

At the above figure 8-2 and figure 8-3 are shown all the procedures followed at the algorithm (Matlab software) with the use of LPSP and LLP power criteria, which are described under:

- Initially the appropriate data are inserted (solar irradiance on inclined plane, wind-speed, ambient temperature, load demand, technical data of the components of the hybrid system, and the required probability of loss of power supply LPSP*).
- For the simulations it is used a wind turbine with rated power 500W.
- Initial batteries capacity is set C_{bat}=10kWh (833,33Ah, 12V).

  → Simulations are conducted with an AGM battery type with a depth of discharge equal to 80% of the nominal capacity.
- A PV module of 1m^2 area and with rated power 140W is inserted.

  → The following process is repeated for 8760hr (1 year).
  - Calculation of the produced energy by the PV (E_{PV}), the wind turbine (E_{WG}), and the total produced (Etot).
  - When the total produced energy of the PVs and WT is greater than the demand then the surplus energy is stored at the batteries. If the batteries are fully charged during the procedure, $C_{bat,max}$, then the rest energy produces excess energy.
  - At the opposite, when the total produced energy is inferior of the loads demand, then the rest energy required is provided by the batteries. Hence, if the stored energy is adequate then the level of batteries capacity is reduced at $C_{bat}(t)$, else a failure occurs and the part of the loads that isn't satisfied is calculated (LPS) and the capacity of the batteries becomes minimum, $C_{bat}(t)=C_{bat\_min}$*.
  - For the equality of the produced and consumed energy no variation of the battery capacity occurs.

  → Calculation of LPSP. If the estimated LPSP doesn't coincides with the desired then the iterative loop begins again and a PV module (1m^2) is added. This process stops only when desired LPSP is achieved (required values as Excess Energy, PV number, batteries capacity etc. are stored).
- Next battery capacity increases with a step of 1kWh (83.33Ah, 12V) and the process is repeated once again until the required LPSP* is reached and till the batteries capacity takes its maximum designated value.
- Finally, by means of the economic study the optimum system is derived.

* For the case with the LLP evaluation criterion when the produced power of the generators and the stored energy at the batteries is inadequate then a failure is counted. The algorithm then calculates the LLP value by adding all the occurring failures and divide them by the total simulating hours (T=8760hr).

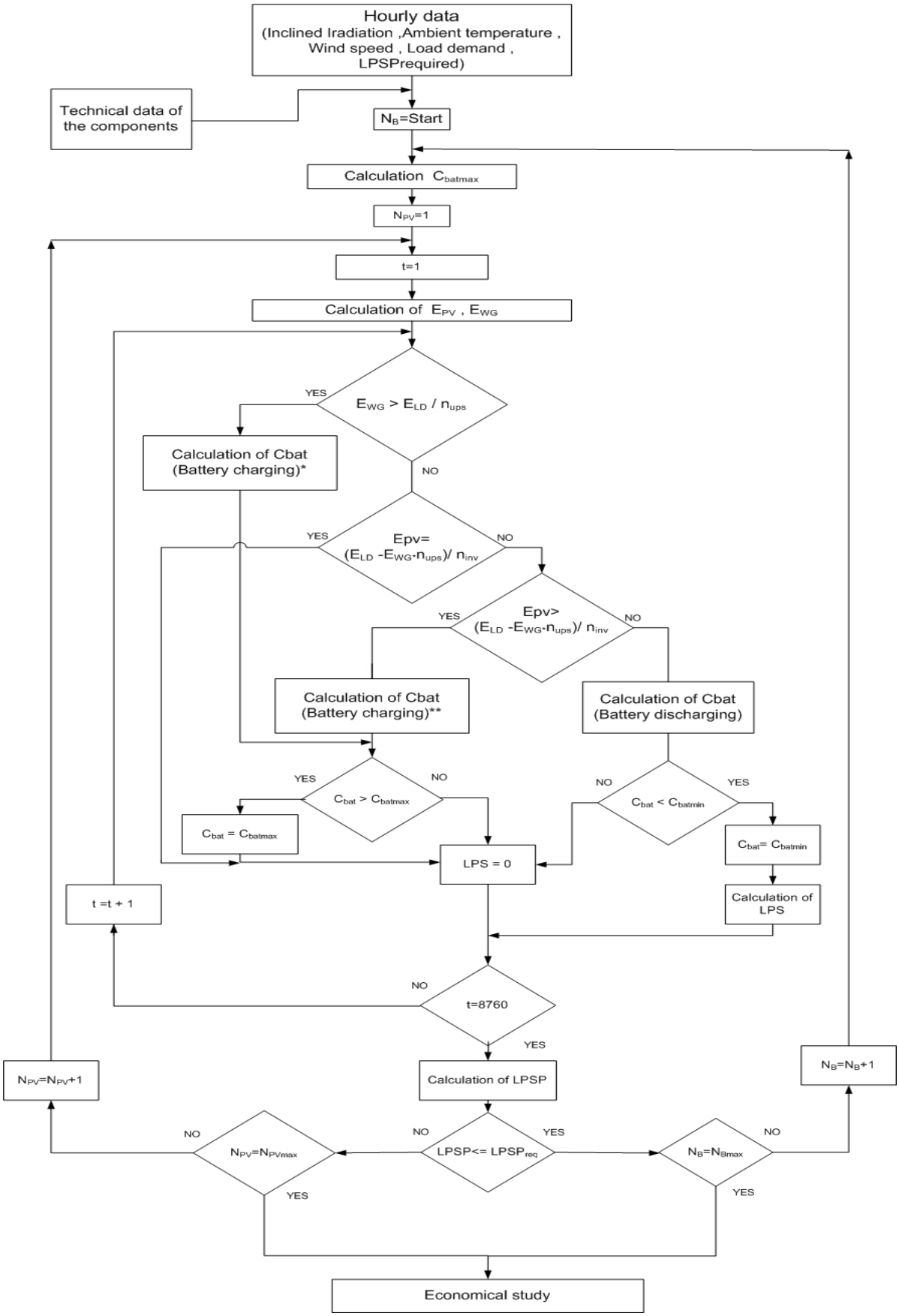


Figure 8-4 Flowchart for the sizing of the hybrid system with UPS and with LPSP power evaluation criterion.

Figure 8-4 illustrates the process for the algorithm which is performed for the sizing and optimization of a hybrid system that uses the wind turbine as the primary generator that provides power to the loads through a UPS.

- Initially the appropriate data are inserted (solar irradiance on inclined plane, wind-speed, ambient temperature, load demand, technical data of the components of the hybrid system, and the required probability of loss of power supply LPSP).
- For the simulations it is used a wind turbine with rated power 500W.
- Initial batteries capacity is set C_{bat}=10kWh (833,33Ah, 12V).

→ Simulations are conducted with an AGM battery type with a depth of discharge equal to 80% of the nominal capacity.

- A PV module of 1m^2 area and with rated power 140W is inserted.

→ The following process is repeated for 8760hr (1 year).

- Calculation of the produced energy by the PV (E_{PV}) and the wind turbine (E_{WG}).
- When the produced energy by the WT is greater than the load demand, then the surplus energy, by the WT, and the energy produced by the PV generator is stored at the batteries*(eq. 8.25). If the batteries are fully charged during the procedure, $C_{bat,max}$, then the over plus remained energy produces excess energy.
- Else if the produced energy by the WT is lower than the loads demand:
  - If the produced energy by the PV equals to the remaining amount of energy of the difference between load demand and the subtraction of that offered by the WT, then no variation on the batteries level occurs.
  - In case where the produced energy by the PVs is greater than the remaining requested load demand, batteries are being charged by the remaining amount of energy, and only till its maximum capacity is reached** (eq. 8.26). The surplus energy after the fully charging of batteries produces excess energy.
  - Otherwise, if the energy provided by the PVs falls short than the remaining requested load demand, the residual amount of energy that is asked is provided by the batteries which are being discharged. If the energy of the discharging process is inadequate ($C_{bat}<C_{batmin}$) then Cbat becomes minimum and loss of power supply (LPS) is calculated.

→ Then LPSP is calculated. If the estimated LPSP doesn't coincides with the desired value then the iterative loop begins again and a PV module (1m^2) is added. This process stops only when desired

LPSP is achieved (required values as Excess Energy, PV number, batteries capacity etc. are stored).

- Next battery capacity increases with a step of 1kWh (83.33Ah, 12V) and the process is repeated once again until the required LPSP* is reached and till the batteries capacity takes its maximum designated value.

Finally, by means of the economic study the optimum system is derived.

9 RESULTS AND DISCUSSION

9.1 ASSESSEMENT OF RES SYSTEM COMPONENTS

In order to take the decision about the appropriate renewable energy system, a comparison between PV individual, wind individual and hybrid PV-wind systems is carried out. This comparison took place with the hourly-based weekly profile and LPSP=5%. For the hybrid system it is chosen only one WT to take place. The obtained systems are evaluated with their power output as a function of batteries capacity and optimized by levelized cost of energy (LCE).

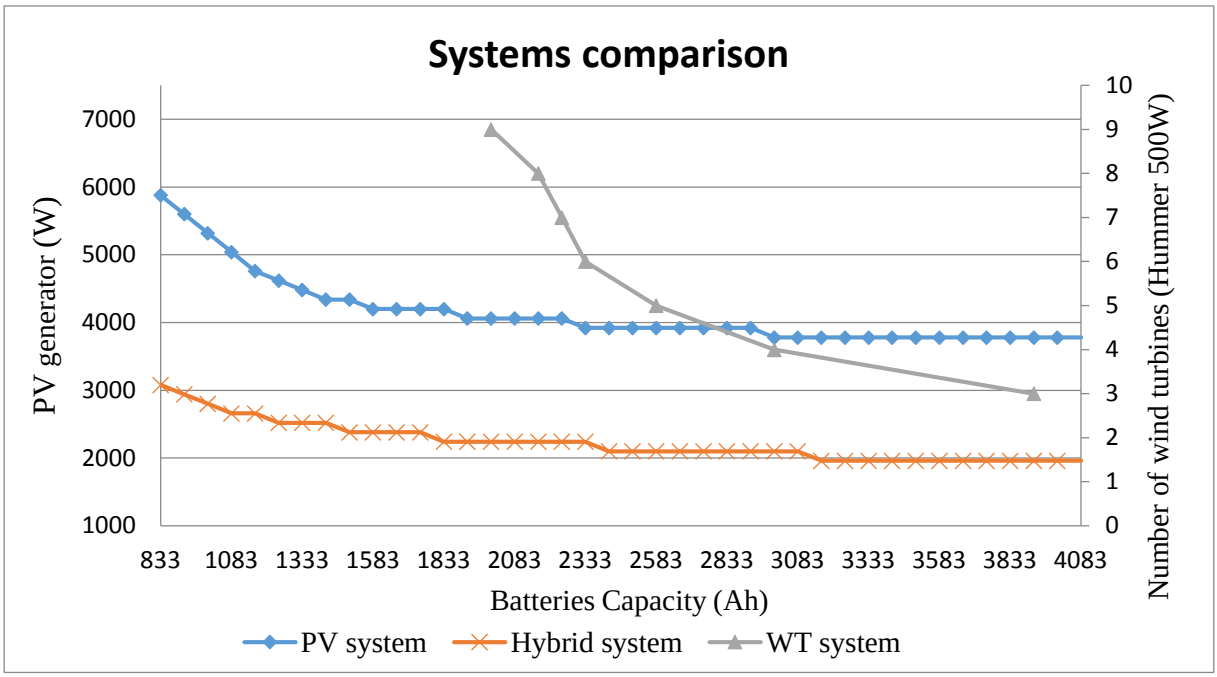


Figure 9-1 Power output of the systems as a function of batteries capacity.

The system with the wind turbines fulfilled the requirements only when it reached the three wind turbines for the predefined maximum batteries capacity being 4083Ah. Therefore at figure 9-1 the number of WT is ranging from 3 to 9, where 9 is the maximum number that the system is examined. For the PV system it is produced almost twice generator than hybrid for all batteries capacities.

These systems are optimized under the levelized cost of energy and the net present value for the life span. Hybrid and PV systems found with the lowest LCE values (figure 9-2) at the most cases and only for batteries capacity greater than 3916Ah the PV system takes a higher value than the WT only system. The last one produces constantly negative NPV (figure 9-3). Hybrid system takes always values that are greater than the PV only system. Hence, the hybrid system it is found to be the best solution with the finest NPV being equal to 3678€ at batteries capacity of 833Ah.

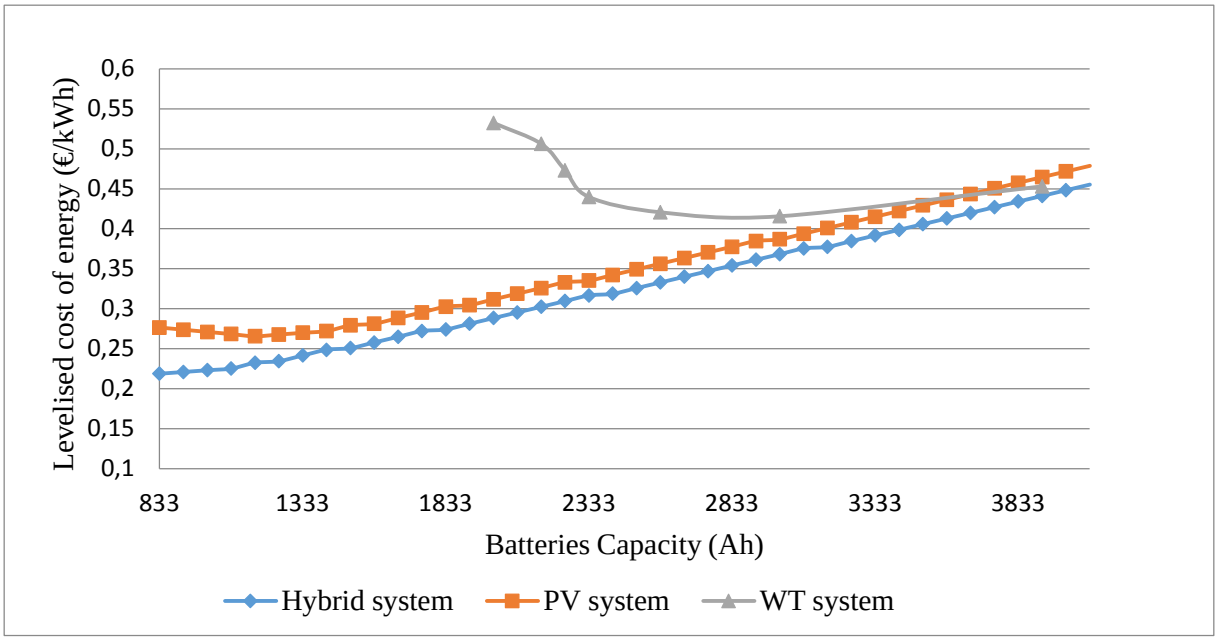


Figure 9-2 Levelized cost of energy for the systems under examination, PV, WT, and Hybrid.

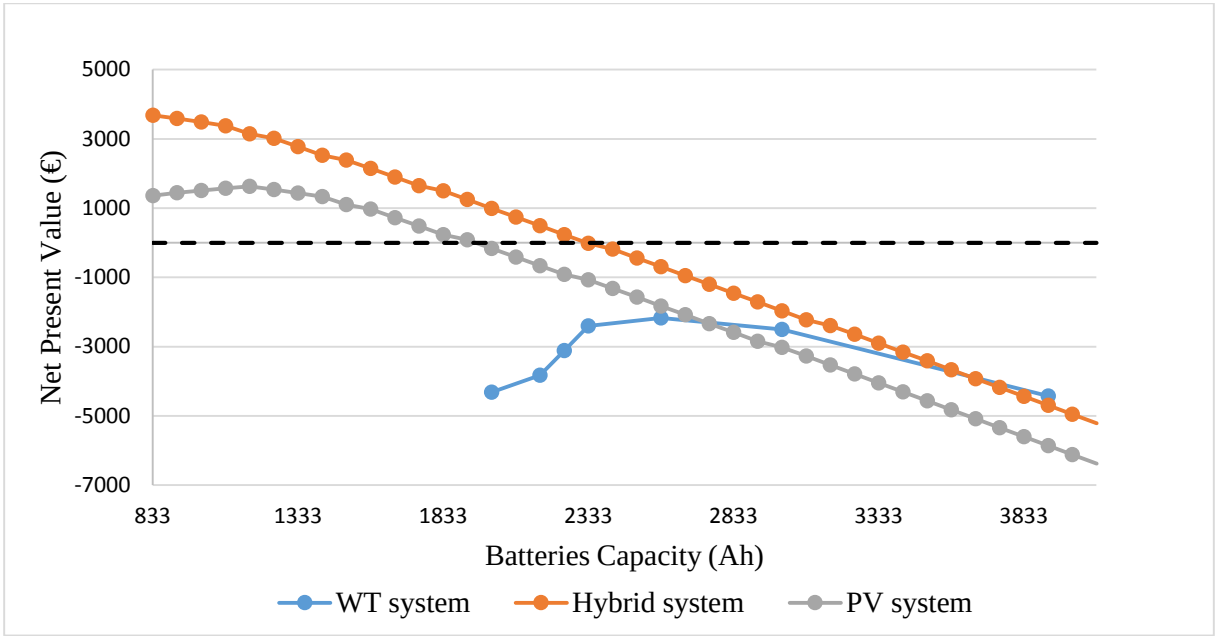


Figure 9-3 Net present value for the systems under examination, PV, WT, and Hybrid.

Next, at table 9-1 the optimum systems that achieved are presented. From the comparison of hybrid and PV system we can see that the hybrid system appears with a LCE 21% lower and a NPV 56% higher, which definitely reveal that the hybrid is the best choice, as the wind individual system presented with a negative NPV which means that the system is uneconomic.

Table 9-1 Optimum obtained configurations for PV individual, WT individual and hybrid PV-wind system with battery bank.

	PV generator (W)	Number of WT (Hummer 500W)	Battery Capacity (Ah)	LCE (€/kWh)	NPV (€)
Hybrid System	3080	1	833	0,219	3678
PV individual	4760	-	1167	0,266	1626
Wind Turbine individual	-	3	3000	0,416	-2500

9.2 RESULTS OF COMPARISON OF ITERATIVE DYNAMIC SIMULATION AND GRAPHICAL CONSTRUCTION APPROACHES

Markvart produced a simplified method to estimate the size of a PV-wind system considering the energies derived by the sun and wind, monthly mean daily average values. The plane's inclination angle was taken at 36° and the wind speed at the hub height of the chosen wind turbine, 23m. The loads demand was set at 10kWh per day.

The monthly means of average daily solar and wind energy is presented at Figure 9-4.

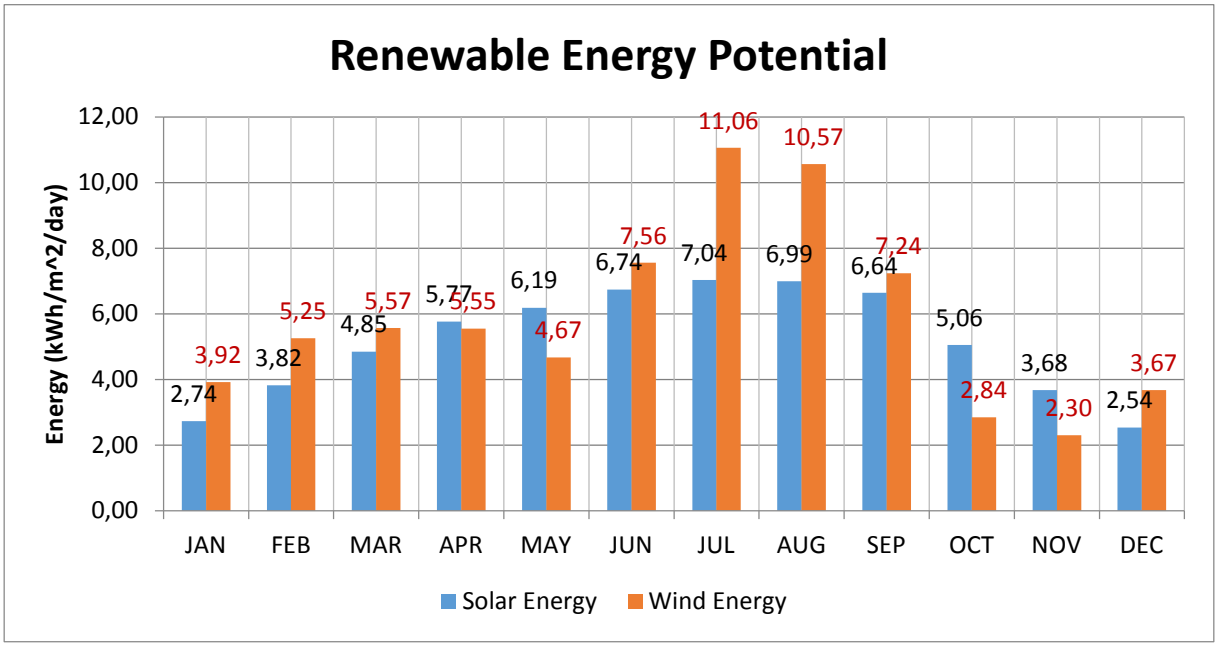


Figure 9-4 Monthly means average daily solar and wind energy, in Rhodos Greece. Solar energy data are for tilted plane at 36°, and wind data are transposed to the hub height, 23m.

By the help of eq. (8.17) it is formed the following set of inequalities where the loads demand is given by the sum of the products of the wind energy with the wind turbine size added with the solar energy with the modules size.

$$\begin{cases} 10 \le 3.92 \cdot a_w + 2.74 \cdot a_H \\ 10 \le 5.25 \cdot a_w + 3.82 \cdot a_H \\ 10 \le 5.57 \cdot a_w + 4.85 \cdot a_H \\ 10 \le 5.55 \cdot a_w + 5.77 \cdot a_H \\ 10 \le 4.67 \cdot a_w + 6.19 \cdot a_H \\ 10 \le 7.56 \cdot a_w + 6.74 \cdot a_H \\ 10 \le 11.06 \cdot a_w + 7.04 \cdot a_H \\ 10 \le 10.57 \cdot a_w + 6.99 \cdot a_H \\ 10 \le 7.24 \cdot a_w + 6.64 \cdot a_H \\ 10 \le 2.84 \cdot a_w + 5.06 \cdot a_H \\ 10 \le 2.30 \cdot a_w + 3.68 \cdot a_H \\ 10 \le 3.67 \cdot a_w + 2.54 \cdot a_H \end{cases}$$

The system above produced the possible solutions for the case that is studied here and presented at figure 9-5.

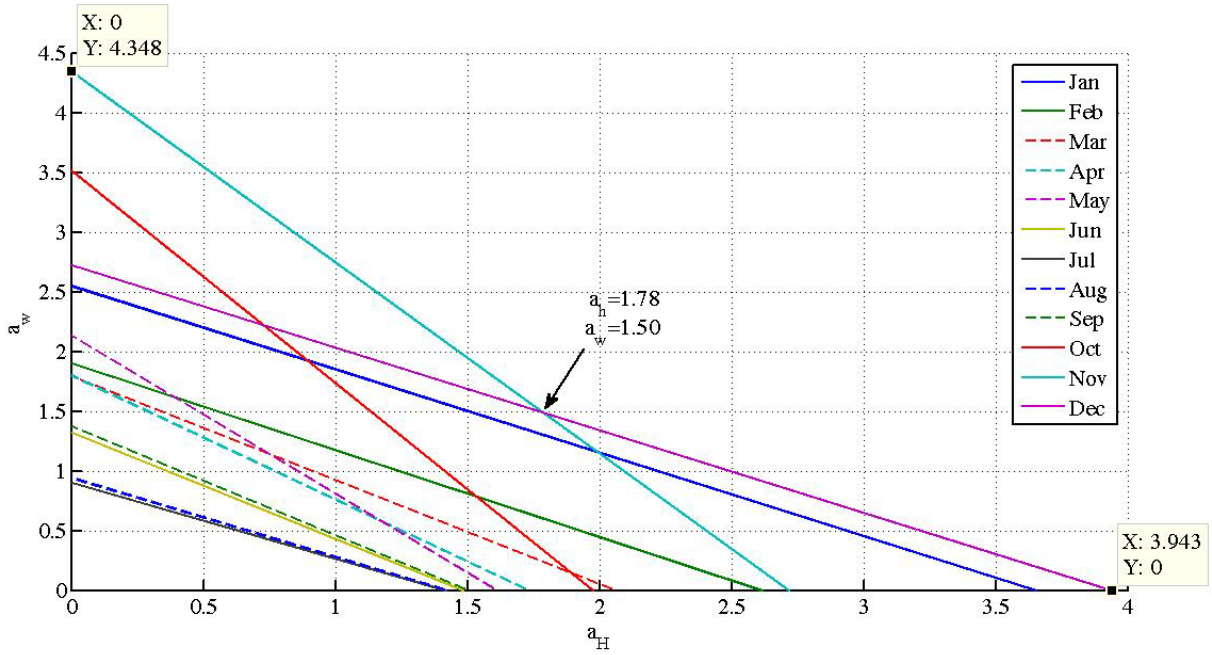


Figure 9-5 The hybrid system created by the monthly analysis with Markvart method for the monthly analysis.

As seen from the graphical presentation the possible systems are only three, PV individual, wind individual and a hybrid consisted of PV-wind. The size of the PV generator was calculated a_H=3.943 and for a PV module equals to 1m^2 and 140W$_{peak}$ the total number is 29 modules, as for a single module a_H=0.14. For the system that is consisted of wind turbines individually it is calculated a_w=4.348 or

in the case with hummer wind turbine, where equals to a_w=2.36 for a single one, then 2 WT must be installed. At the vertex that hybrid exists the PV generator is calculated a_H=1.78 and the wind generator a_w=1.50. The number of the PVs for the hybrid is 13 and a_H becomes for the exact PVs equal to 1.82, and the WTs are 1 and a_w is changed to a_w =2.36.

From equation (8.18) the cost of the hybrid it is found:

$Hybrid\ Generator\ Cost = c_H \cdot \alpha_H + c_w \cdot \alpha_w$=760·1.82+625·2.36= 1383.2+1475= 2858.2€

$PV\ Generator\ Cost = c_H \cdot \alpha_H$=760·3.943=2996.68€

$Wind\ Generator\ Cost = c_w \cdot \alpha_w$=625·4.72=2950€

where c_H=760€ and c_w=625€ represent the cost of the PV and wind generators per unit power of the output rating. Consequently, the hybrid system calculated to be the best solution..

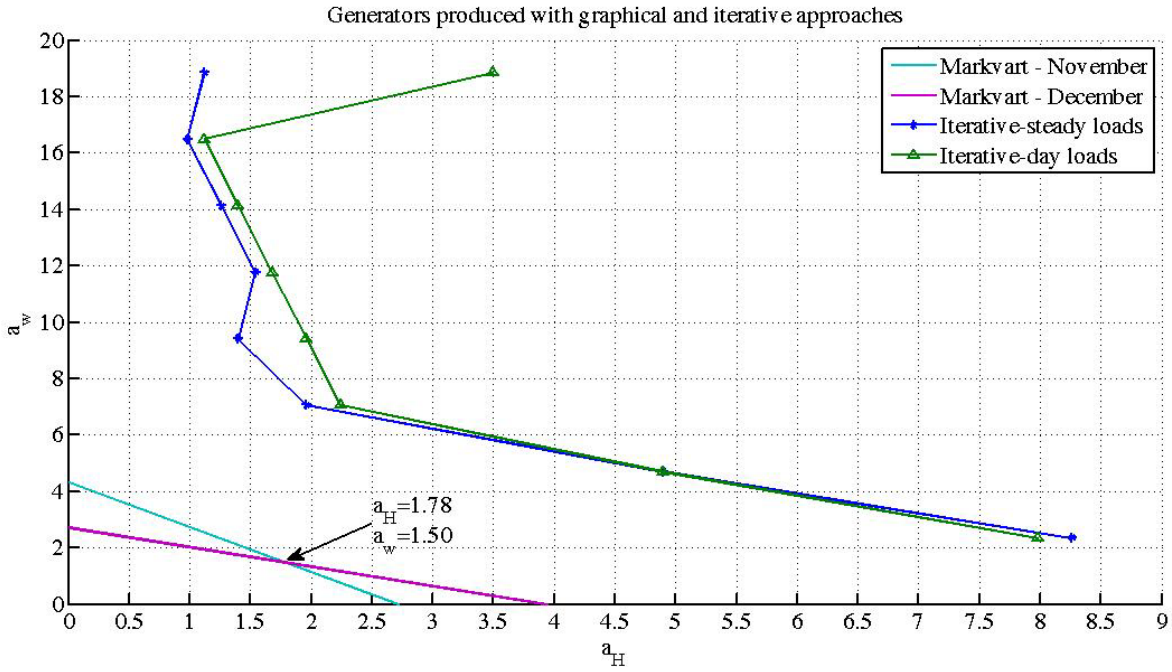


Figure 9-6 The hybrid systems created with the two methodologies, iterative and graphical. For the iterative approaches considered two load profiles one all day steady and the day hourly changing.

Figure 9-6 provides the comparison between the two methods. The iterative approach is done for two different load profiles, one being equal to 0.416kW and steady all day long, and the other one is the day profile shown at figure 7-7, with LPSP=0.

Table 9-2 Systems calculated for different number of WT with the best LCE for each case and LPSP=0 with steady load profile.

STEADY LOAD							
Wind Turbines		PV modules		C_{bat}		LCE	NPV
N_{WT}	a_w	N_{PV}	a_H	N_{BAT}	C_{bat} (Ah)		
1	2,36	59	8,26	15	1250,033	0,456793	-3973,8
2	4,72	35	4,9	27	1916,753	0,443036	-3377,96
3	7,08	16	1,96	40	2916,833	0,472259	-4330,33
4	9,44	10	1,4	42	3000,173	0,507086	-5187,88
5	11,8	11	1,54	18	3083,513	0,545224	-6079,52
6	14,16	9	1,26	42	3166,853	0,58279	-7003,38
7	16,52	8	0,98	43	3250,193	0,620355	-7927,25
8	18,88	25	1,12	42	2250,113	0,658493	-8818,89

The systems produced at all cases are the optimum systems obtained for the referenced number of wind turbines. Resulting systems are much higher than those presented by Markvart. Also, as can be seen from the tables the PV generators decreases partially, except the last one, at which PVs were increased because there is a decrease at batteries capacity.

Table 9-3 Systems calculated for different number of WT with the best LCE for each case and LPSP=0 with day load profile.

DAY LOAD							
Wind Turbines		PV modules		Cbat		LCE	NPV
N_{WT}	a_w	N_{PV}	a_H	N_{BAT}	C_{bat} (Ah)		
1	2,36	57	7,98	15	1250,033	0,425784	-2853,86
2	4,72	35	4,9	23	1916,753	0,414765	-2324,34
3	7,08	16	2,24	35	2916,833	0,443988	-3276,71
4	9,44	14	1,96	36	3000,173	0,481553	-4200,57
5	11,8	12	1,68	15	3083,513	0,519118	-5124,44
6	14,16	10	1,4	38	3166,853	0,556683	-6048,31
7	16,52	8	1,12	15	3250,193	0,594249	-6972,17
8	18,88	25	3,5	27	2250,113	0,632387	-7670,44

Markvart is a simplified method for hybrid PV-wind systems sizing. It estimates only the size of the generators without taking into account any other part of the system, batteries, inverters and converters. Also, Markvart doesn't considers the effect of the temperature on PVs efficiency, or the wind speed cut-in and cut-out of the WT. By using mean daily monthly values its approach doesn't takes into consideration hours or days without energy production at all. The calculation of costs doesn't counts the life of the system, the costs of the remaining parts of the system, installation costs, maintenance and replacement as well as factors such as inflation. At the opposite the iterative method takes into

account all these parameters and the results obtained are more accurate than those of graphical illustration method, although they have greater values.

9.3 EVALUATION OF THE EFFECT OF THE TWO TECHNICAL PARAMETERS OF LLP & LPSP

Considering the configuration as presented at figure 7-9, the simulation runs for two technical parameters, LLP and LPSP. The first one results in times of system failures, and the other calculates the exact power that couldn't be satisfied. They are compared for different portions of the load demand that is asked for to satisfy, being 0%, 5% and 10%, in hourly and daily incremental and adopting a profile that hourly-based weekly.

9.3.1 LLP=0 and LPSP=0

In this case the comparison of the two parameters gives a fully autonomous RES system. The simulation carried out to provide all the power required, at hourly intervals, by the loads. Next the results will be presented for a steady number of wind turbines being equal to one, and the calculation of the PVs will be presented. Economic evaluation is also provided.

The first figure 9-7 gives the optimal configurations for different capacities of the batteries. The algorithm begins with a minimum storage of 10 batteries and fully charged, in order to meet the loads in case that there is no or low energy produced from the generators at first day, and stops at the number of 50. Both methods resulted in identical systems, the one with the markers pointing LLP method and the line the LPSP. Definitely, this is justified as there is no technical constraints inserted in the algorithm, cluing in something different.

With a glance it is figured out that with the first configuration and the initial batteries we get a large PV generator that equals to 18.76kW$_{peak}$ (134 modules of 140W$_{peak}$, as taken). Then, there is a steep drop of the power of the PVs as the number of the batteries rises, till the point we have batteries capacity 1417Ah (17 batteries of 83,33Ah) and PV generator size gets a value 8.68kW. An average drop of 1.44kW occurs per battery added till that point.

The last calculated batteries capacity is 4084Ah and the PV generator at that time found to be 4.76kW. The reduction of the generator is less than 4kW, although they were added batteries of extra capacity 2667Ah, given that a much lower rate of decreasing (0.13kW/battery added).

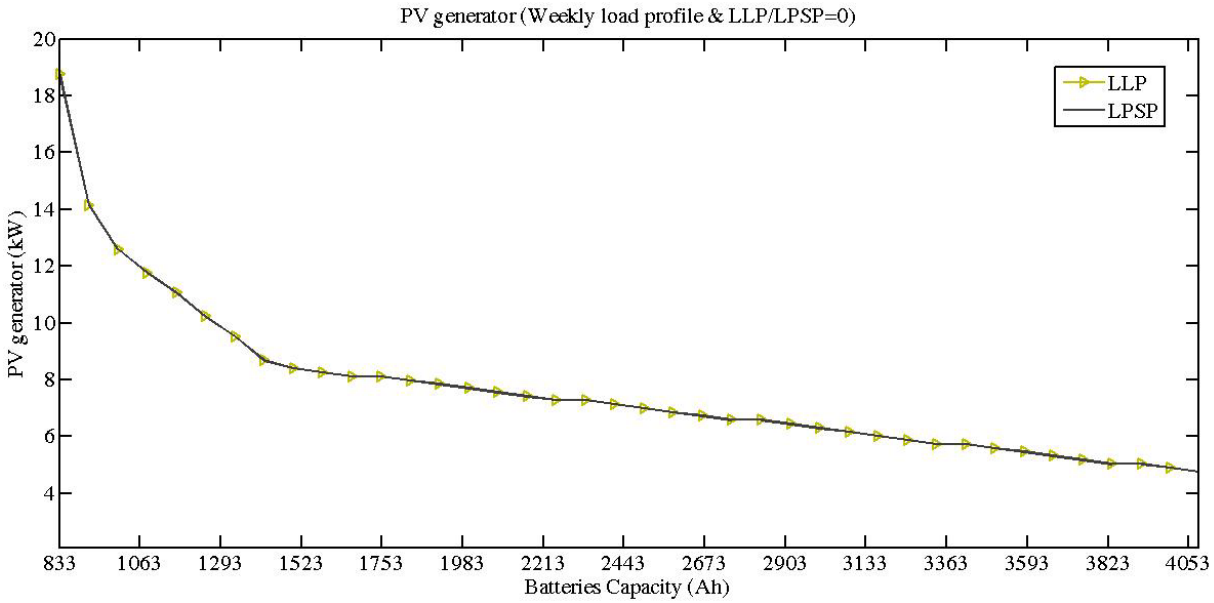


Figure 9-7 Hybrid system configurations with hourly load profile (changing every day of the week) and LLP//LPSP=0.

Having all these configurations obtained, and considering of the excess energy, by means of the energy that left over after satisfying the loads and fully charging the batteries, it is shown at figure 9-8.

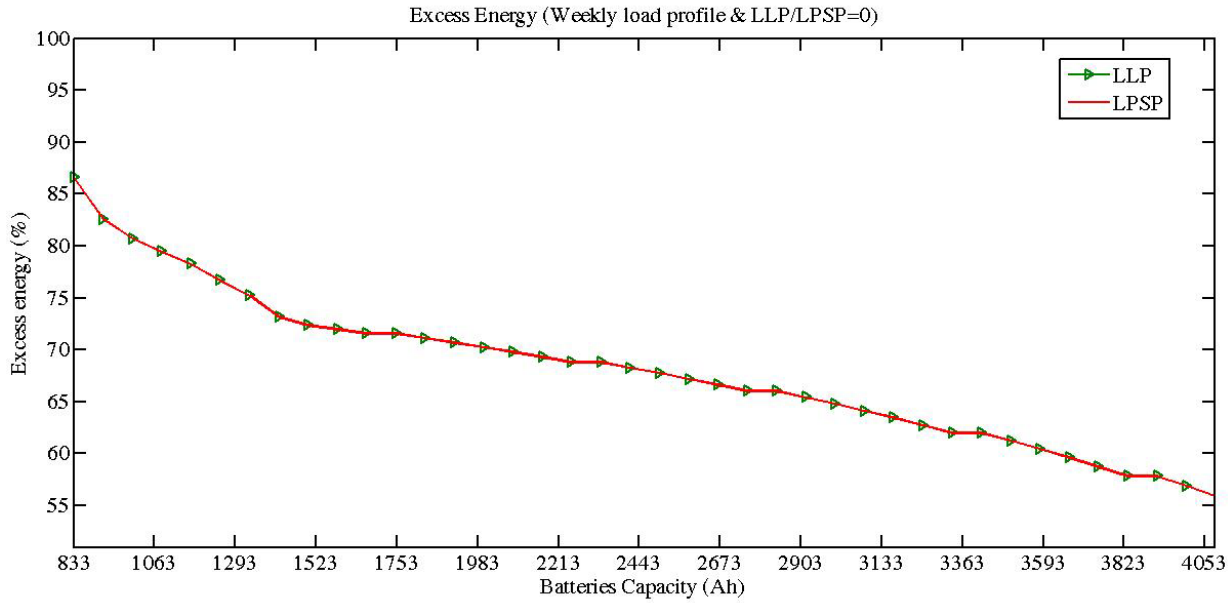


Figure 9-8 Excess energy generated from the configuration per batteries capacity.

At the above figure we can see a likeness with figure 9-7. The excess energy reduces in an almost linearly way, and this reduction is caused by the lower PV generators produced when batteries increasing.

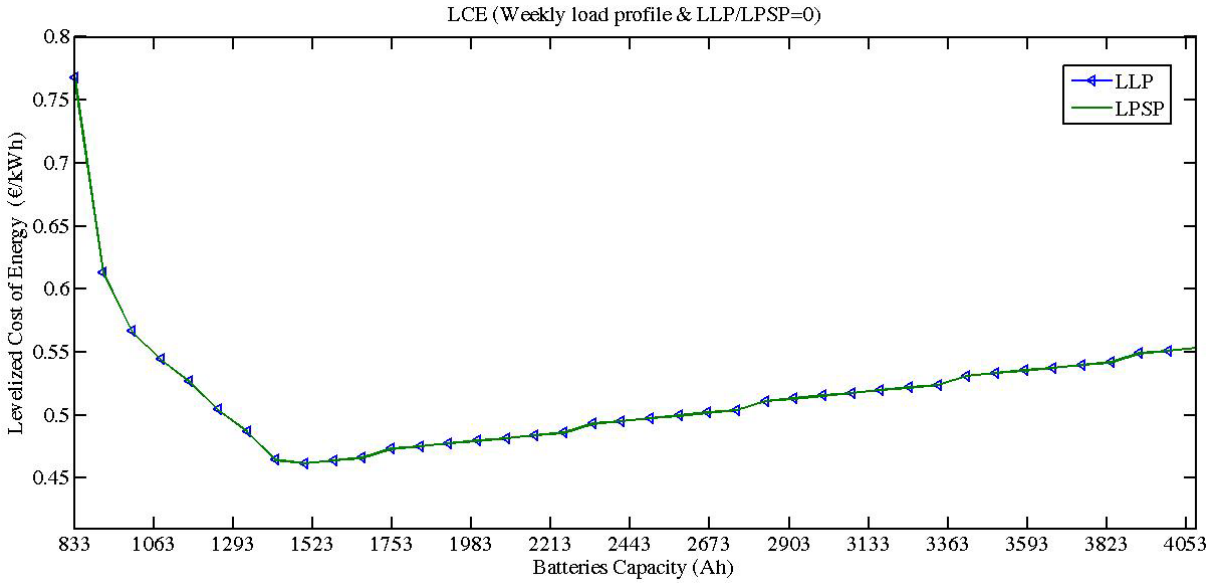


Figure 9-9 Levelized cost of energy is depicted in this figure for all the obtained configurations.

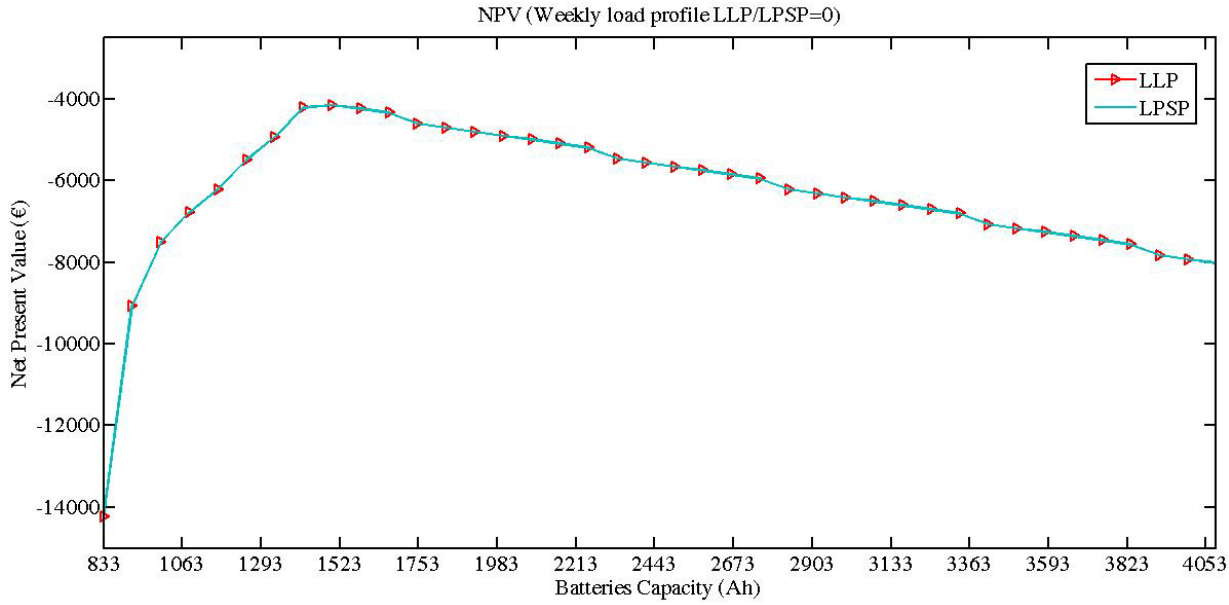


Figure 9-10 Net present value as estimated per system produced for different capacities.

The optimization of the system under the economic criteria of LCE and NPV resulted in identical results between the two technical approaches. In Greece, the cost of electricity is received 0.22€/kWh, including taxes and others[21]. Hence, at figure 9-9 the lowest value that is created is 0.4617€/kWh, with the configuration consisted of a wind generator of 0.5kW, PV generator 8.4kW and batteries capacity 1500Ah. Even then, the system is not viable comparing to the cost of electricity provided by the public electricity utility provider. To make this more clear, the investment becomes negative at the amount of -4139€ for the best case.

[21] The cost of the electric energy statistically is increasing in a rate of 3% annually (http://ec.europa.eu/eurostat/statistics-explained/index.php/Main_Page).

9.3.2 LLP=5 and LPSP=5

In this part a comparison between the two technical parameters is done, and the loss probability set 5%.

In this case we can see that LLP produces greater generator and partially congregating with LPSP method at highest batteries capacities (figure 9-11). LLP needs are 5 extra PV modules, 18% higher, at the initial situation and finalizes with only 1 extra at the final state, differentiates 6.7%. At no case coinciding each other.

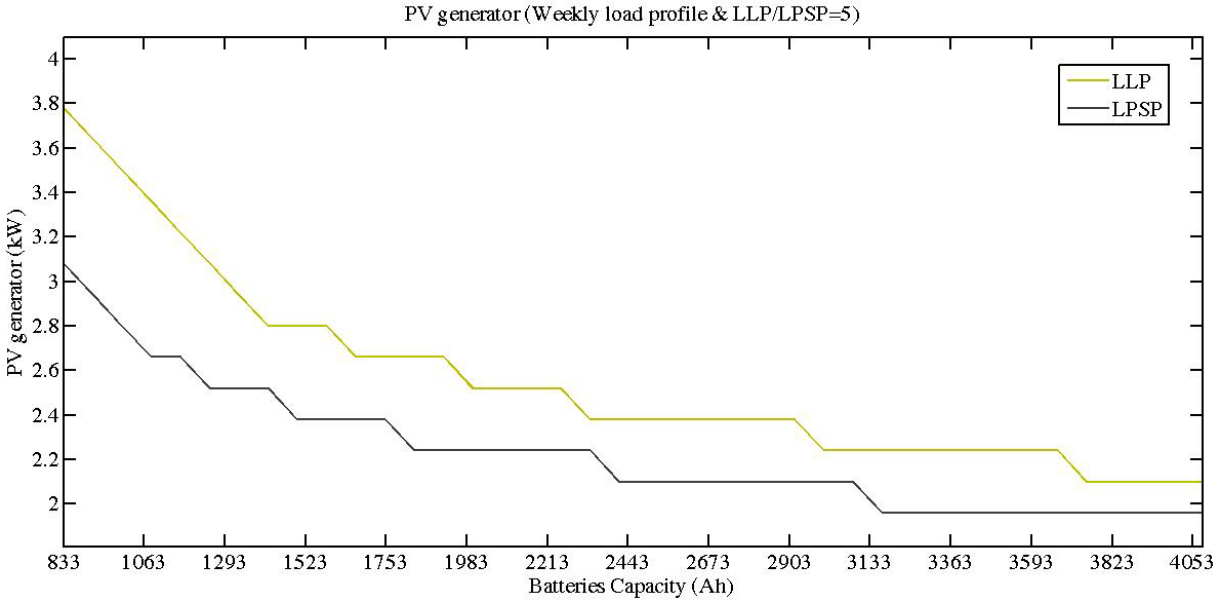


Figure 9-11 The PV generator peak power produced with different technical parameters (LLP & LPSP) with different capacities and one wind turbine 0.5kW$_{peak}$.

Examining the wasted energy produced by the calculated systems, LPSP method systems exploit the energy sources to satisfy the loads in a better manner (figure 9-12).

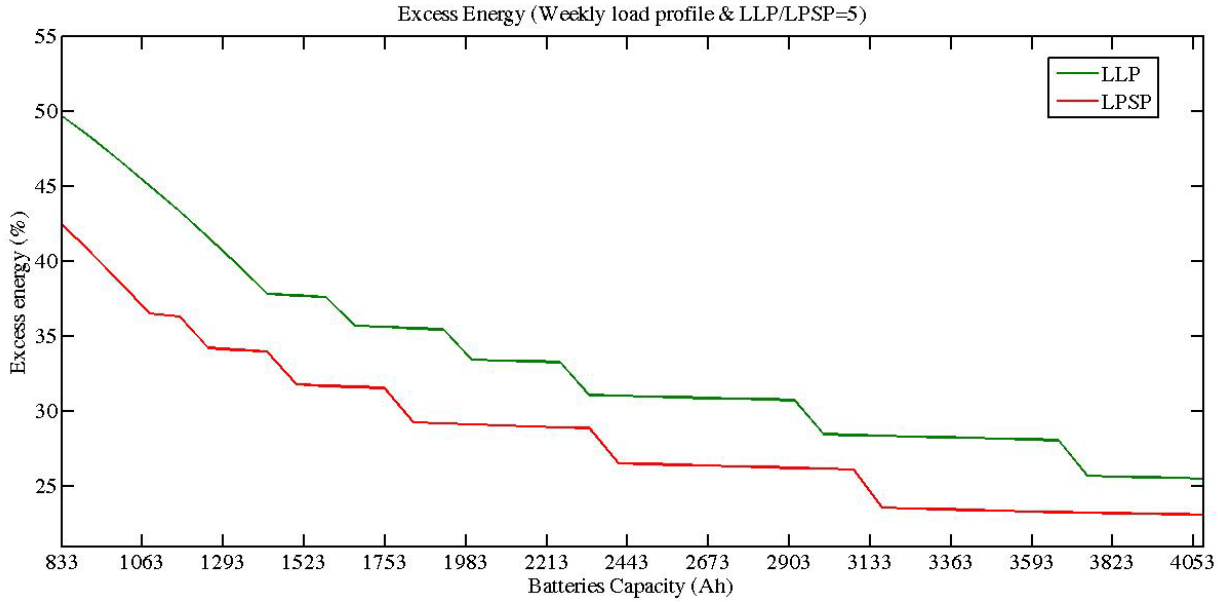


Figure 9-12 Excess energy produced per system with LLP//LPSP=5%.

From an economic aspect LCE and NPV gives more efficient systems with the LPSP method. So, for the optimal systems of each method we found a difference that equals to 0.025€/kWh, with LLP being higher (figure 9-13).

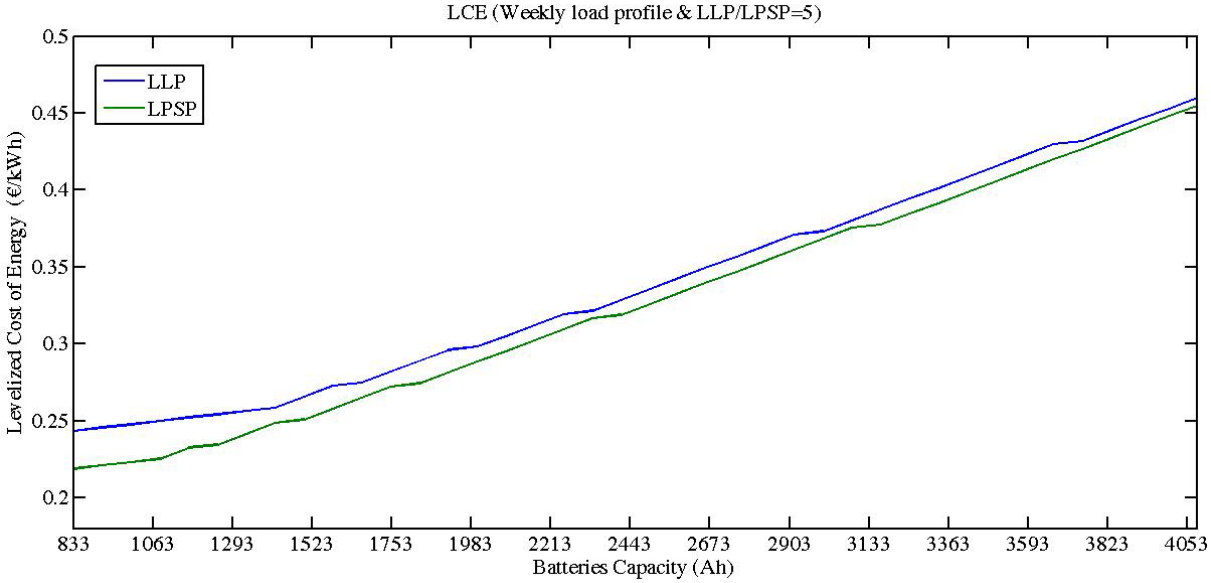


Figure 9-13 Economic evaluation of the system with LCE (€/kWh) and storage banks.

NPV at the optimum point was calculated 3678€ with LPSP and 2837€ with LLP method (figure 9-14). The configurations per case have storage capacity of 833Ah, and PV power 3.78kW and 3.08kW, for LLP and LPSP respectively.

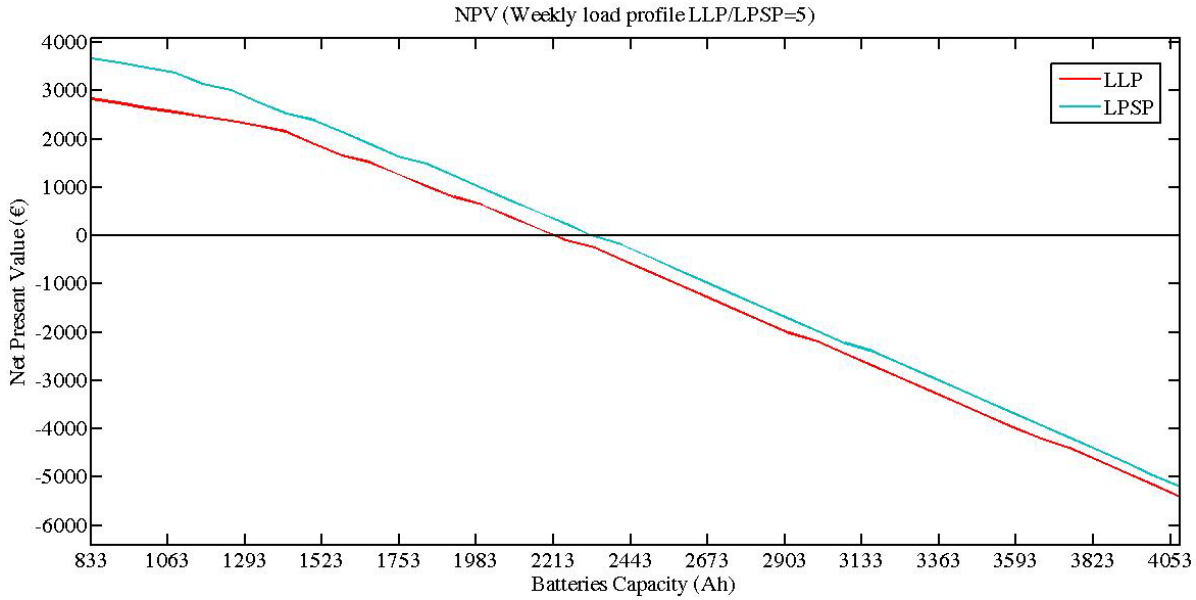


Figure 9-14 Net present value of the system for LLP/LPSP equal to 5%.

9.3.3 LLP=10 and LPSP=10

Here, it is examined the case with the constraint of loss probability at 10% and the following diagrams were obtained for PV generator power and excess energy as shown in figure 9-15 and figure 9-16, respectively.

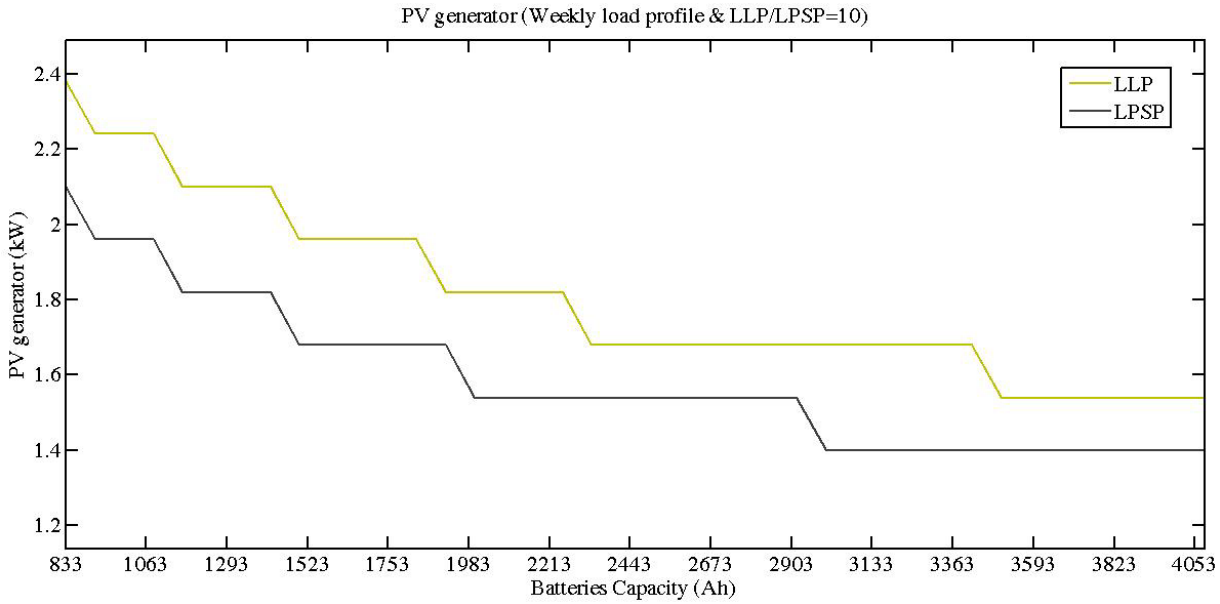


Figure 9-15 Systems configurations with LLP or LPSP equal to 10% versus batteries capacity (Ah).

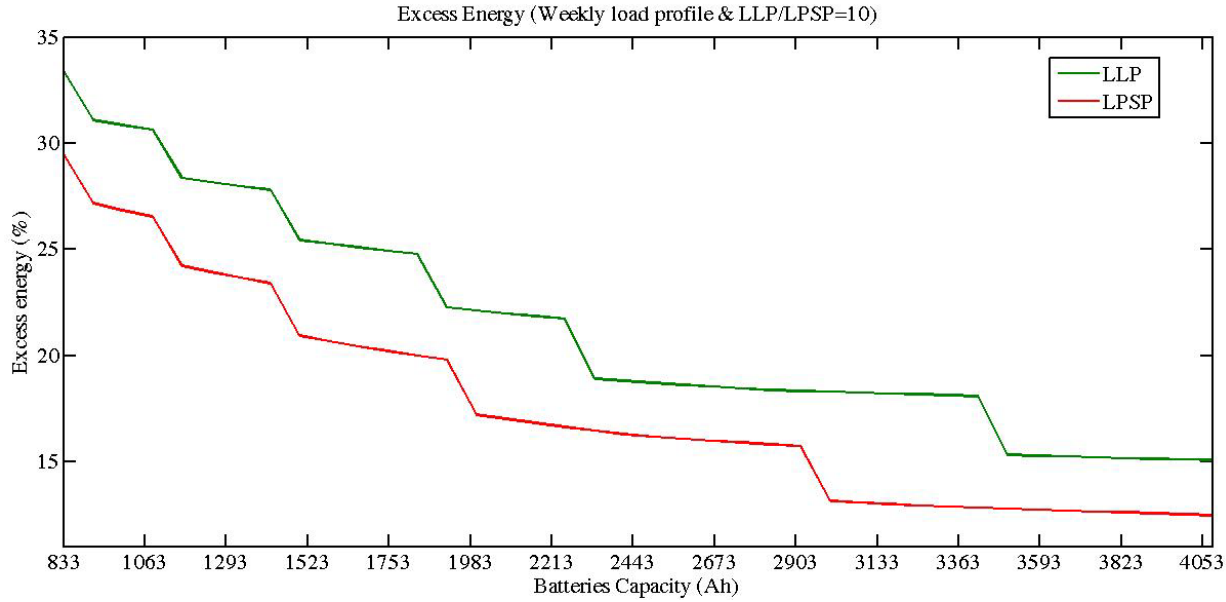


Figure 9-16 Excess energy produced per system case and technical parameter of LLP and LPSP.

Like the previous case, LPSP gives lower generators for all simulated storage capacities. At the initial system the difference of the PV power is calculated at 12% and for the final batteries capacity 9%, with LPSP providing the lower values (figure 9-15).

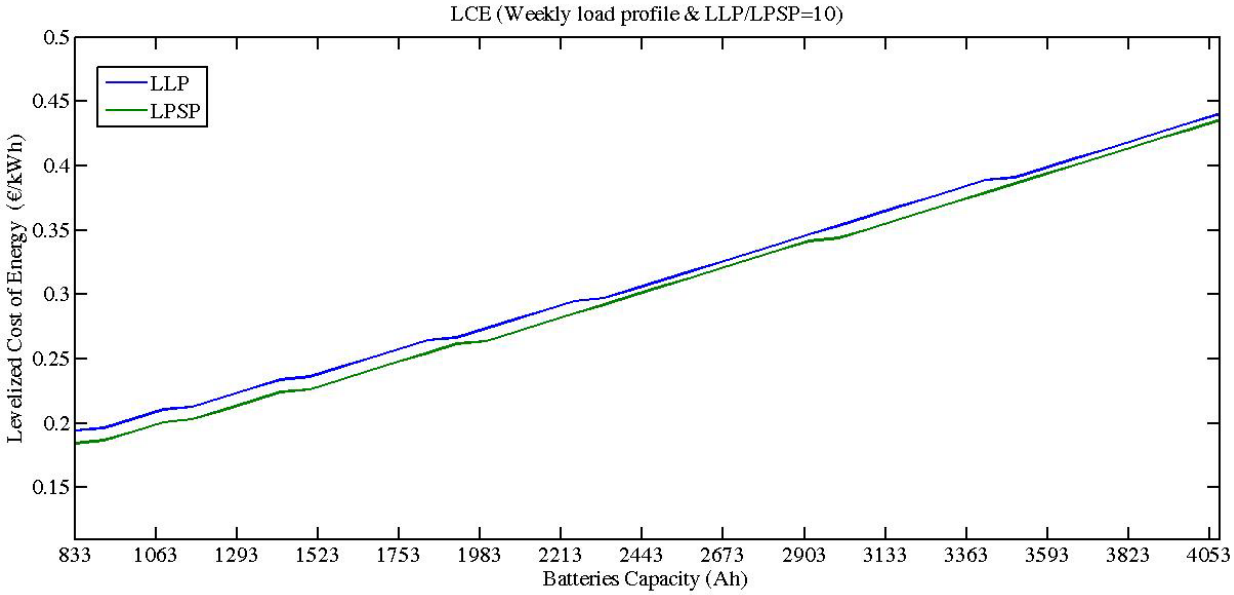


Figure 9-17 LCE for the two constraints LLP/LPSP=10.

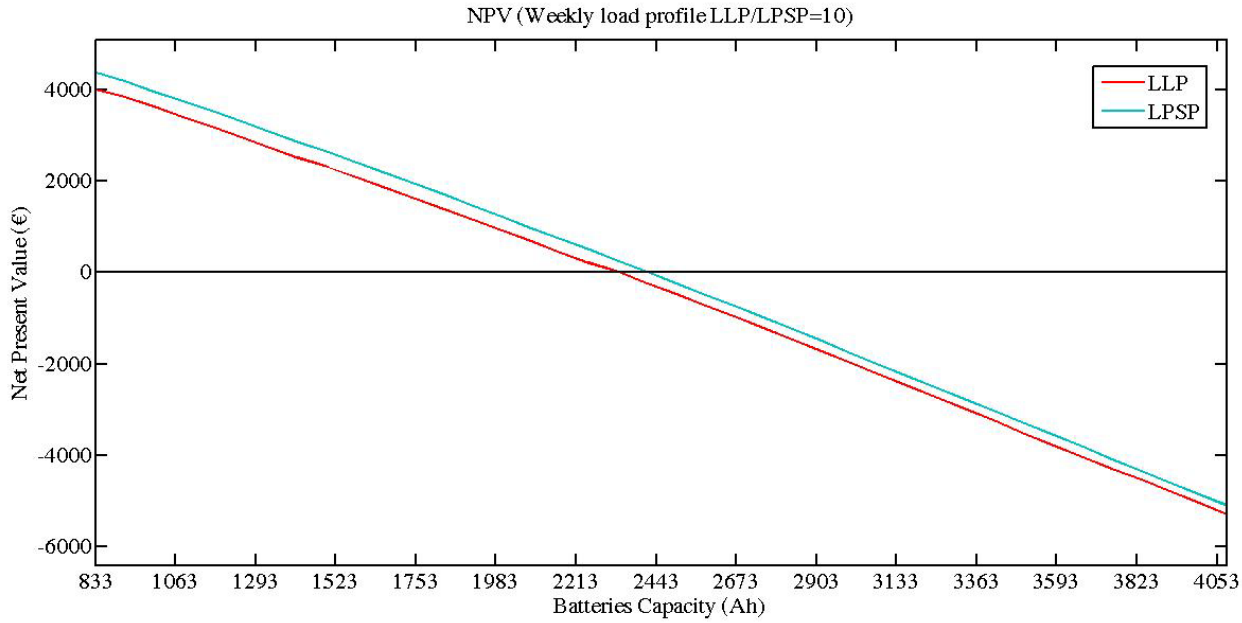


Figure 9-18 Net present value for the acquired systems for different batteries capacities.

LCE is presented with values being at the optimum configuration 0.1943€ and 0.1845€ with LLP and LPSP respectively, and with storage bank capacity 833Ah (figure 9-17). As it seen from (figure 9-18) the produced systems for capacities over 2417Ah are not viable, at both LLP and LPSP. At the optimum configuration becomes higher than 4000€ in both cases, reaching the values of 4010€ (LLP) and 4375€ (LPSP).

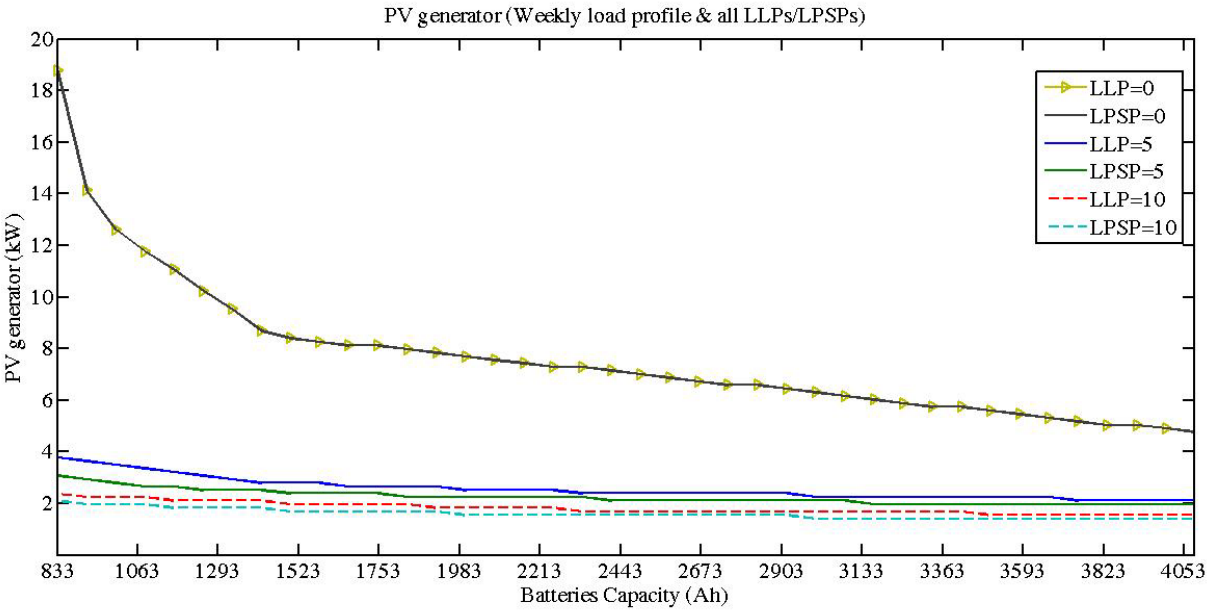


Figure 9-19 PV power produced for all LLPs and LPSPs.

At figure 9-19 they are depicted the PV generators for all LLPs and LPSPs under consideration. The results shown, from the first value of loss probability being 0% with the next 5%, a decrease of 80% for LLP for 833Ah batteries capacity to 56% for 4083Ah, and for LPSP 84% (833Ah) and 59% (4083Ah). Then for the value of 10% there was a further decrease of the generators ranging from 37% to 27% for the first and last batteries capacities with LLP and 32% to 29% with LPSP, respectively. Obviously, there is a steep drop of the generators of the PVs when the loss probability increases, and those extracted with the LPSP parameter were even more reduced.

At the table 9-4 under are presented the optimum systems obtained for each case for LLP and LPSP. In all simulations it is taken one wind turbine with rated power output 500W (Hummer).

Table 9-4 At this table are presented all the optimum systems per case for both LLP and LPSP.

LLP/LPSP	PV Generator (kW)		Excess Energy (%)		Battery Capacity (Ah)		LCE (€/kWh)		NPV (€)	
(%)	LLP	LPSP	LLP	LPSP	LLP	LPSP	LLP	LPSP	LLP	LPSP
0	8,40		72,39		1500		0,46		-4138,69	
5	3,78	3,08	49,71	42,49	833	833	0,24	0,22	2837,37	3678,03
10	2,38	2,10	33,38	29,50	833	833	0,19	0,18	4010,08	4374,73

9.4 ASSESSMENT OF THE EFFECT OF THE TIME INTERVALS AT SYSTEM SIZING AND OPTIMIZATION

Working with the configuration shown in figure 7-9 and adopting the three load profiles (day, night, weekly) that change in hourly intervals, but being constantly equal to 10kWh per day, and one daily, also 10kWh, an approximation of time intervals effect to the size of the acquired system is done. This study considers a loss of power supply probability 5% for all simulations.

9.4.1 Technical evaluation of the system

At figure 9-20 are depicted the generators produced per case. As expected the daily load profile produces constantly the smaller PV generator, than the others. This happens because possible failures during the day haven't been taken into account, as this case considers the total energy produced and delivered to the loads per day. When batteries capacity reaches 1917Ah the day and daily profiles presented with alike PV plants due to load demand gathering at sunny hours and the capability of the batteries to satisfy higher amounts of loads at the afternoon or at the night. Night and weekly profiles produce equal PVs almost constantly. The last two gave the higher generators for all batteries capacities. The night load profile presented to have a PV generator 17.4% greater than day profile with the initial batteries capacities (833Ah); and the day profile is higher than daily close to 10.5%. Finalizing, with the highest batteries capacities the two night with weekly, and the day with daily get the same PVs. Among the two couples there is a difference at PV generators around 7%, with the couple day-daily being higher.

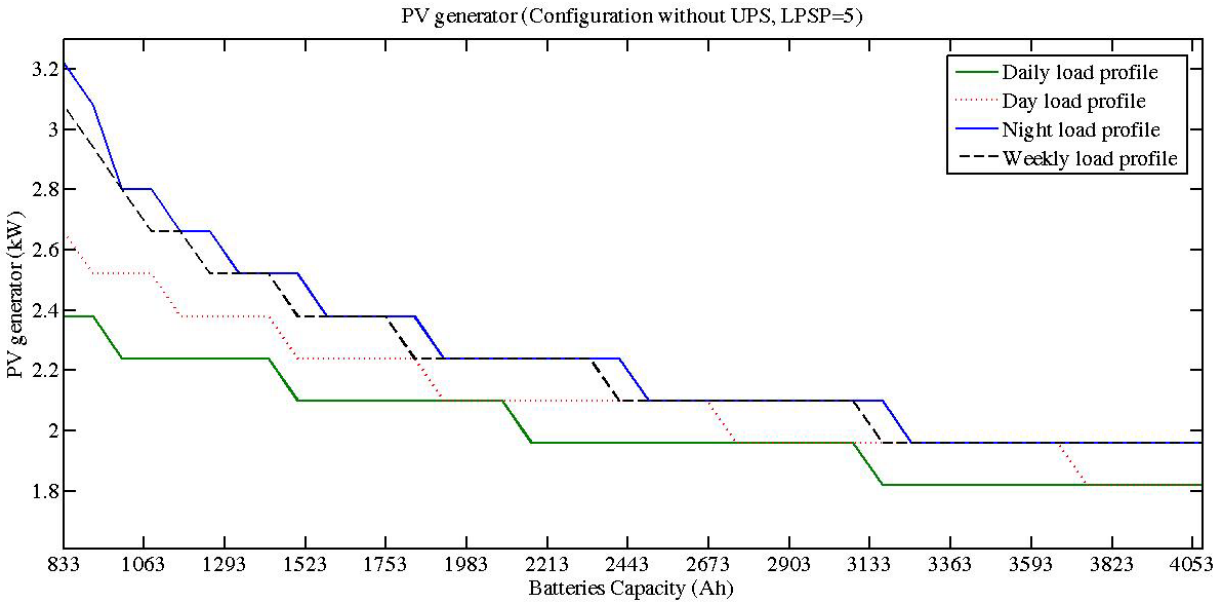


Figure 9-20 PV generators calculated for each load profile by means of day, night, weekly and daily load profile, for the configuration without UPS and LPSP=5.

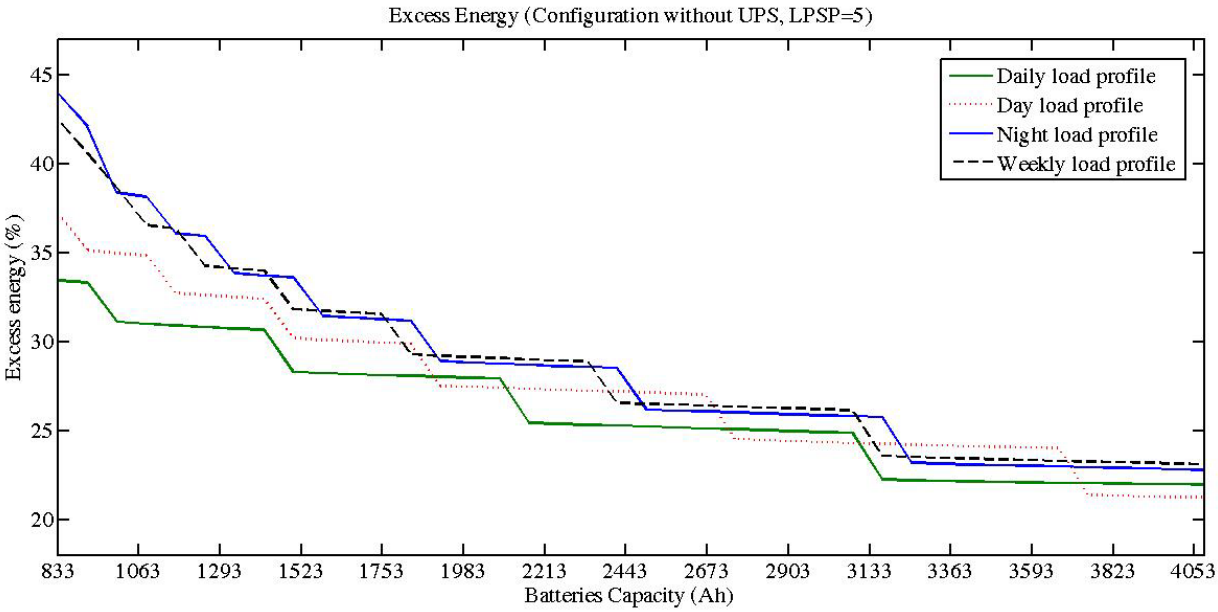


Figure 9-21 Graphical presentation of the results of the produced systems under the technical parameter LPSP=5 for the different load profiles day, night, weekly in hourly intervals and daily constant. All hourly profiles when summed equals to daily (10kWh).

As seen at figure 9-21, night and hourly-based weekly produced the higher amounts of excess energy. The daily, doesn't account the frequency of charging/discharging of the batteries per hour, and therefore the net amount of energy exceeding the loads demand reached, when batteries being fully charged, higher portions for identical systems. For the bigger batteries capacities excess energy converges for a load profiles.

9.4.2 Economic optimization of the system

The viability of the generated systems that fulfill the power reliability constraints should provide the lowest levelized cost of energy, or even more the uppermost net present value. But when an investment is about to be done we should be sure that is correct. How LCE and NPV are affected by different profiles is informative useful for a more accurate decision making.

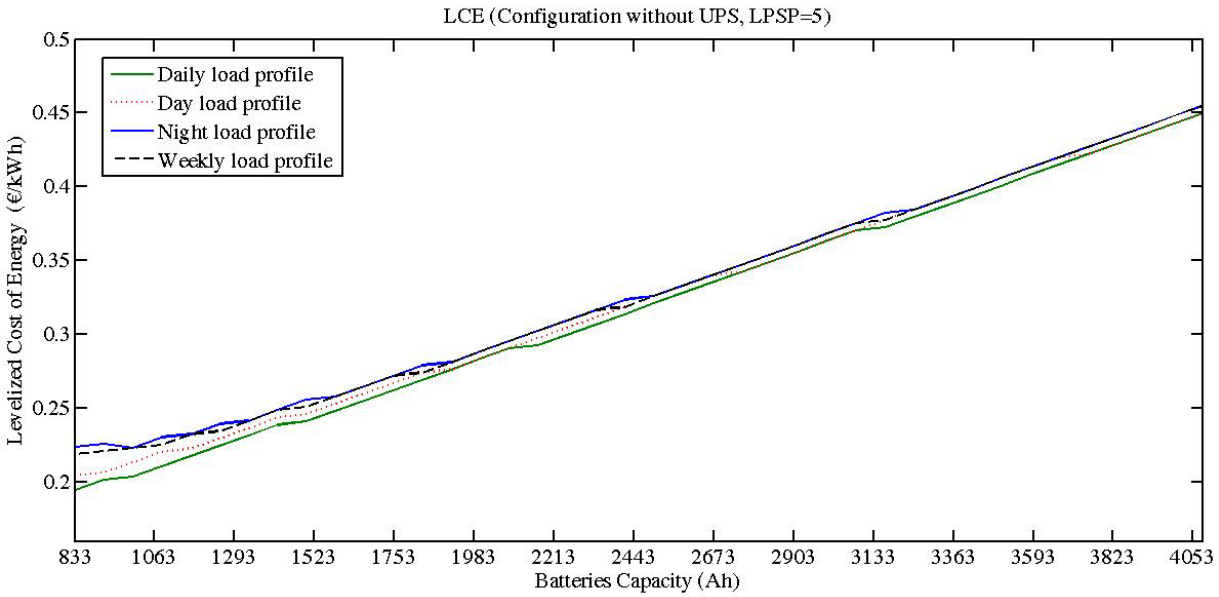


Figure 9-22 LCE as produced for different storage capacities and with different load profiles.

Levelized cost of energy determines the real cost of energy when choosing an investment to be done. Night and weekly profiles are close, almost constantly (figure 9-22). For the optimum configuration the night profile provides a LCE 12.4% bigger than daily. Also, the day profile has a value 4.8% higher than daily.

NPV is discrete in all situations when optimal system happens (833Ah) (figure 9-23). At that point we obtain systems that range from 3509€ to 4521€ for the systems with night and daily profile, respectively. As for the day profile the profit is calculated to be 4199€ and for the weekly 3678€. Hence, the most profitable system is the one with daily profile.

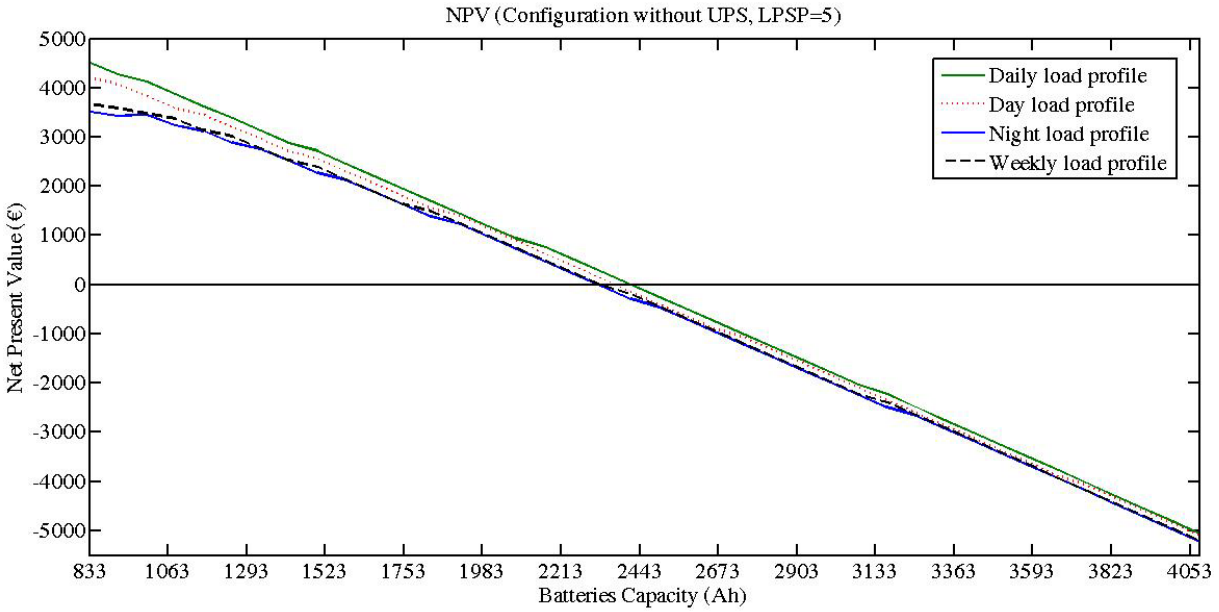


Figure 9-23 NPV is clearly found to be higher with the adoption of daily load profile, and followed by day, night and weekly profiles in series as named.

All the optimum systems obtained with the different load profiles and LPSP=5% are shown at table 9-5. The daily profile produced the lower PV generator. In contrary, the night profile presented with the highest.

Table 9-5 Here are presented the technical and economic characteristics of the optimum systems obtained for the different load profiles (LPSP=5%).

LOAD PROFILES	PV Generator (kW)	Excess Energy (%)	Battery Capacity (Ah)	LCE (€/kWh)	NPV (€)
Daily	2.38	33.43	833	0.1943	4521,00
Day	2.66	37.23	833	0.2041	4199,00
Night	3.22	43.95	833	0.2232	3678,00
Weekly	3.08	42.49	833	0.2188	3509,00

9.5 IMPACT OF THE CONFIGURATION TYPE ON SYSTEM SIZING

After the examination of different technical parameters and the observations arisen from different load profiles results, here a deepening effort about how the configuration of the system affects the sizing and the optimum cases will be derived. In the first the wind turbine is considered as primary source and power is provided directly to the loads via the UPS. At the second one, both PV-WT are primary sources and the loads are satisfied even from either generators or the batteries; the last assists only if the generated energy is beneath the loads demand.

The results of different portions of LPSP, saying 0%, 5% and 10%, are compared via the day and night load profiles, in order to get a better point of view of the generated systems dependence on these factors. Finally, the economic evaluation of the systems is done adopting LCE and NPV.

9.5.1 Evaluation of the system configuration with LPSP=0

As mentioned above both configurations were examined with the two load profiles of day and night. Loss of power probability technical parameter was set equal to 0 and the produced generators are graphically displayed at figure 9-24.

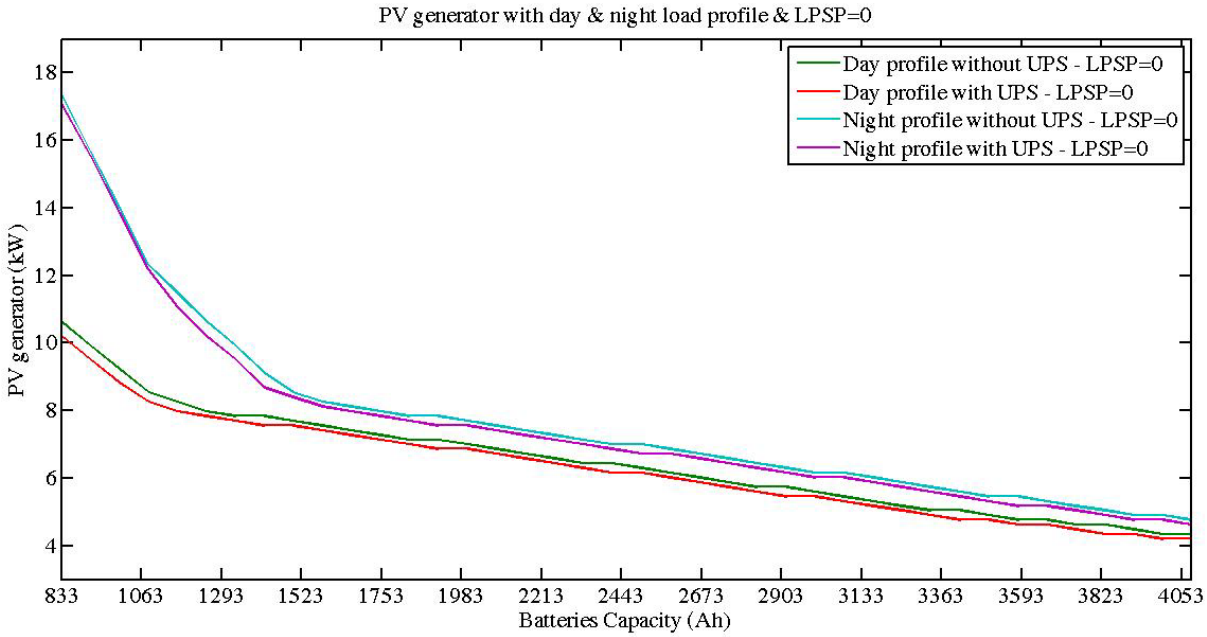


Figure 9-24 At this figure are depicted the different generators produced by the simulation for both generators (figure 7-9, figure 7-10) and taking a loss of load probability equal to zero.

As seen at figure 9-24 the peak powers, with starting batteries capacities at 833Ah, for the occasion of night profile the configuration with the UPS produced lower peak power generator by approximately 1.6% against the one without UPS. For different batteries capacities the variation of the portion of the power difference, for the two configurations with night profile, ranges between 1.6-4.6%, and for the maximum batteries capacities it is calculated to be 3%. This portion for the day profile it was found 3% at most cases, again the system with the UPS being lower.

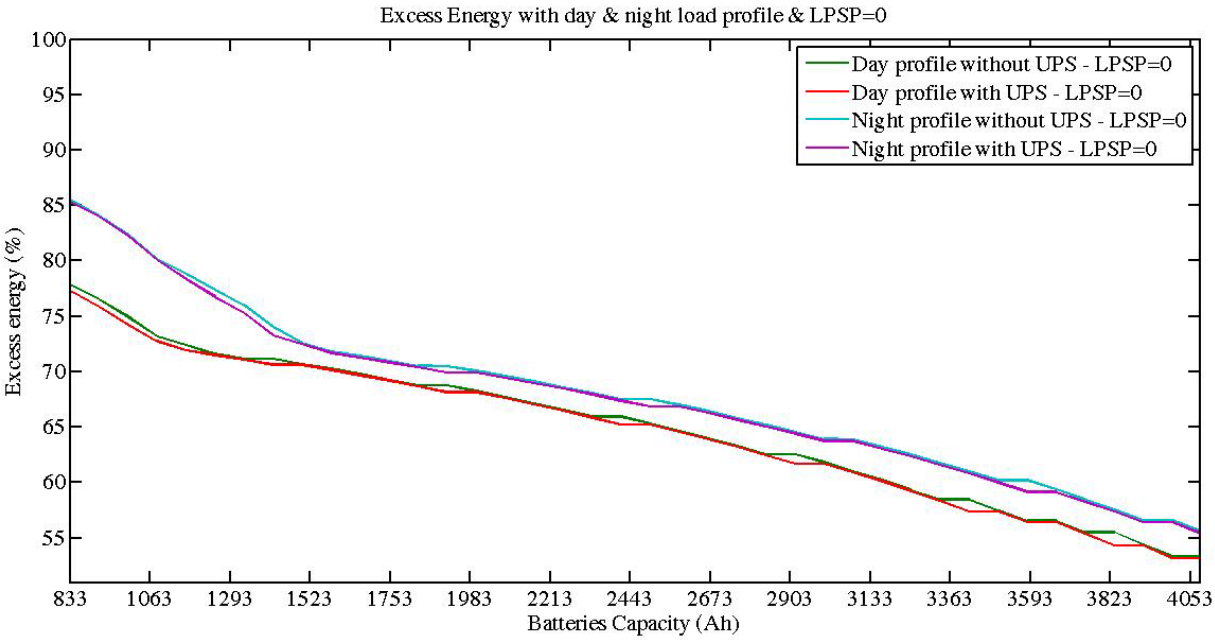


Figure 9-25 Excess energy per system. Higher rates appear for the initial systems ranging between 77.3% (day profile, with UPS) and 85.5% (night profile, with UPS).

The maximum values of PV generators between the two profiles without UPS and with batteries 833Ah, they differentiate just about 38.7%. When the UPS was implemented, the two profiles were derived with a difference of 40.1%, with night producing the higher generator. Among the two configurations, those with uninterruptible power supply give less PV modules at all battery capacities. Excess energy for the systems without UPS are constantly higher than those without at all cases (figure 9-25).

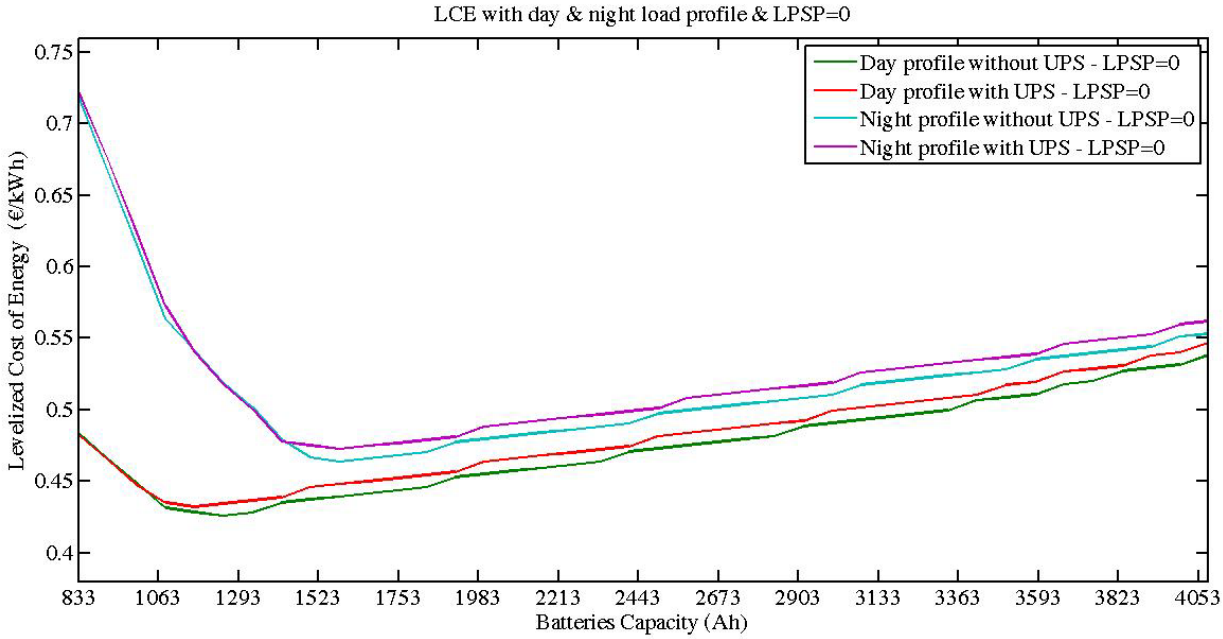


Figure 9-26 LCE has a steep drop at the first configurations but never becomes profitable, for all examined cases.

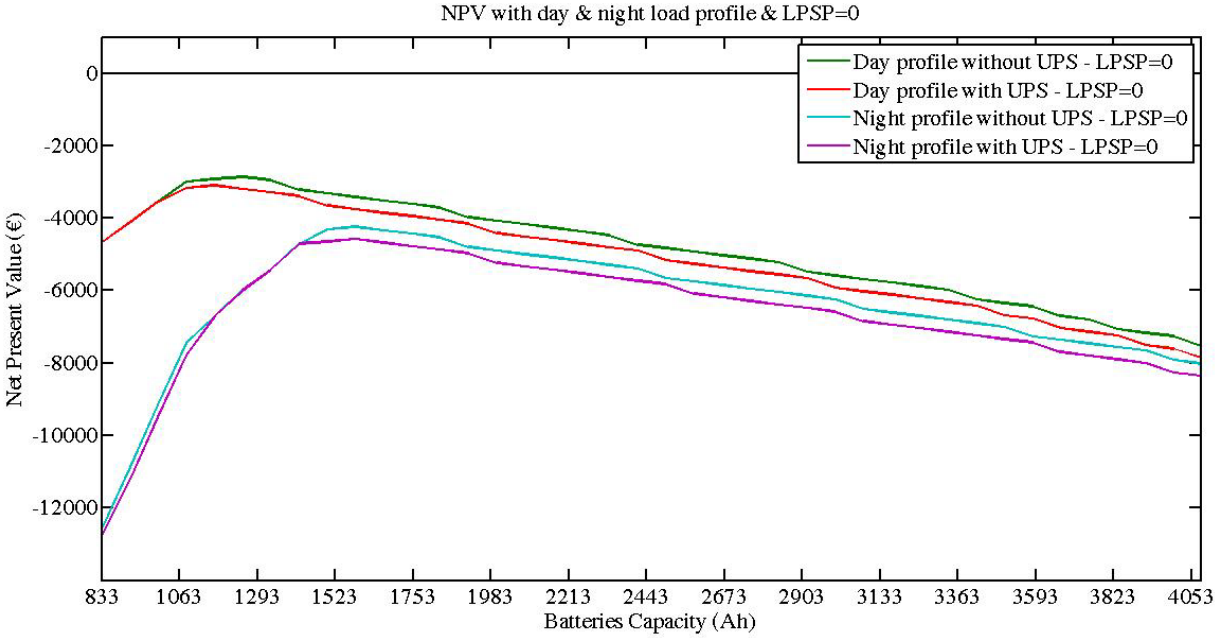


Figure 9-27 NPV clearly shows that the capital recovery never happens for the life span of the RES systems under consideration.

Levelized cost of energy, figure 9-26, calculated higher values for the cases with UPS with both profiles, whereas the produced PV generators for this configuration were lower compared with those without UPS. This is due to the cost of UPS, and the replacements considered at life span. Net present value was negative for all systems and systems were non- viable (figure 9-27).

From table 9-6 we can see almost identical excess energies for all the optimum systems. The PV generators for the day profile and both configurations were the same but for different batteries capacities, 1167Ah with UPS and 1250 without UPS. With night profile the UPS produced one less PV with the same batteries capacity. The system with the lowest LCE, 0.4258€/kWh was that with day profile without UPS.

Table 9-6 In this table are presented the technical and economic parameters for the optimum systems per configuration (with and without UPS).

Configurations	PV Generator		Excess Energy		Battery Capacity (Ah)		LCE		NPV	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
UPS	7.98	8.12	71.94	71.7	1167	1583	0.4322	0.4725	-3094,00	-4576,00
Without UPS	7.98	8.26	71.5	71.81	1250	1583	0.4258	0.4639	-2854,00	-4237,00

9.5.2 Evaluation of the system configuration with LPSP=5

Here the LPSP was set at 5%. Figure 9-28 shows the obtained PV generators for the different load profiles with the two configurations. In general the systems occurred for the configurations without UPS gave higher or identical values of PV generators, and for the two load profiles. For the rest, the day and night profiles presented to get equal generators for the two configurations per profile. Compared to those calculated with LPSP=0 are almost 5 to six times smaller. Also, it must be pointed the fact that night load profiles asked for superior PV plants due to loads mismatching. As batteries capacity increases the resulting generators converges at the same PV generator for the capacity of 4083Ah, except only that with the night profile without UPS that needs one PV extra (14 in total).

Excess energy for the two configurations are displayed with neighboring values (figure 9-29), and for the two load profiles. Only, in the initial batteries capacities the night profile generated higher excess energy due to higher PV generator (with and without UPS).

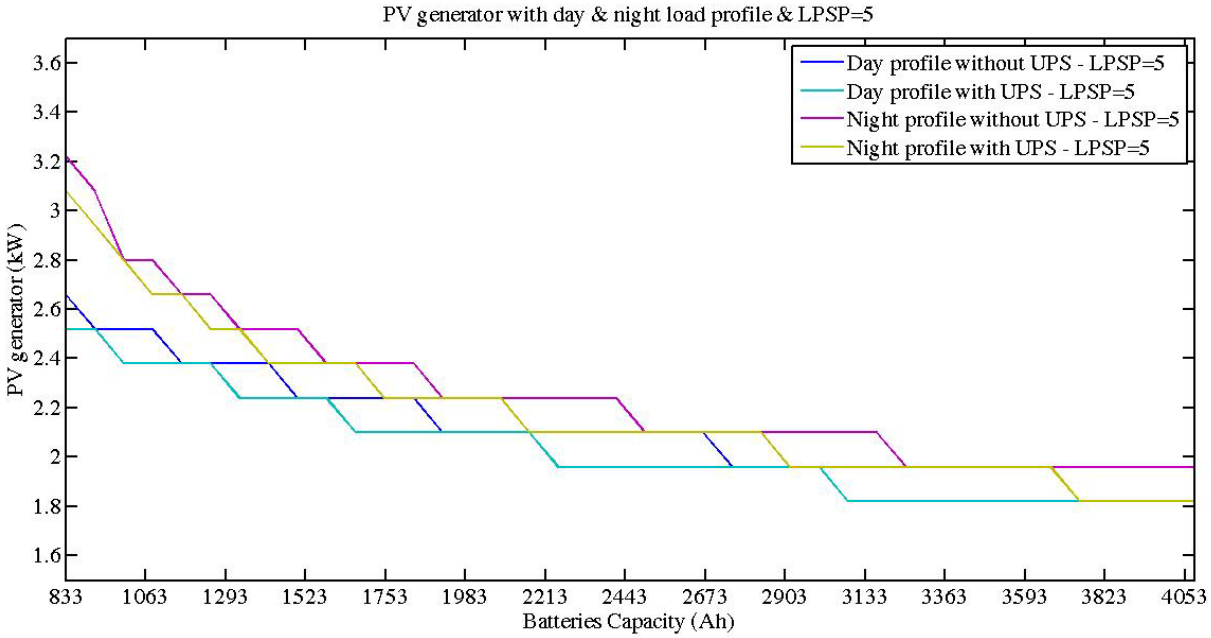


Figure 9-28 At this figure are shown the PV generators peak power per system for the two load profiles, with the two configurations, and a LPSP=5.

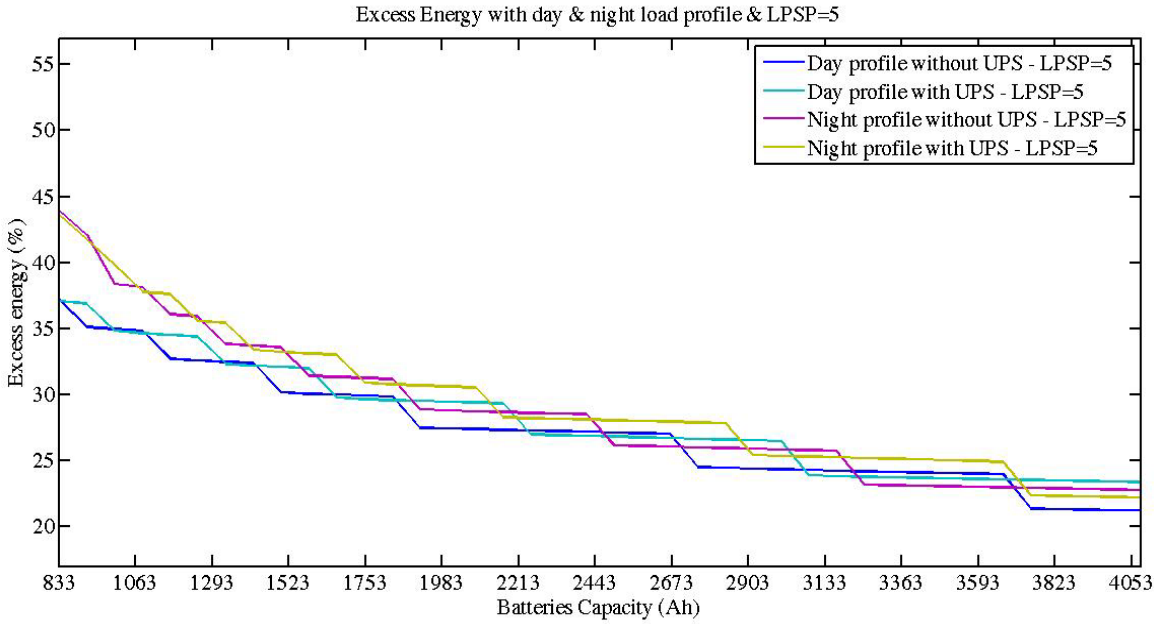


Figure 9-29 Excess energy for the configurations with UPS corresponds to bigger amounts of energy not delivered or stored, for day and night profiles.

The two economic evaluation parameters of LCE and NPV they follow almost linear distribution, as seen at figure 9-30 and figure 9-31. At all systems estimated and for both load profiles the values for these economic parameters appear to have the same difference, with and without UPS. Always the configuration without UPS produced more effective systems.

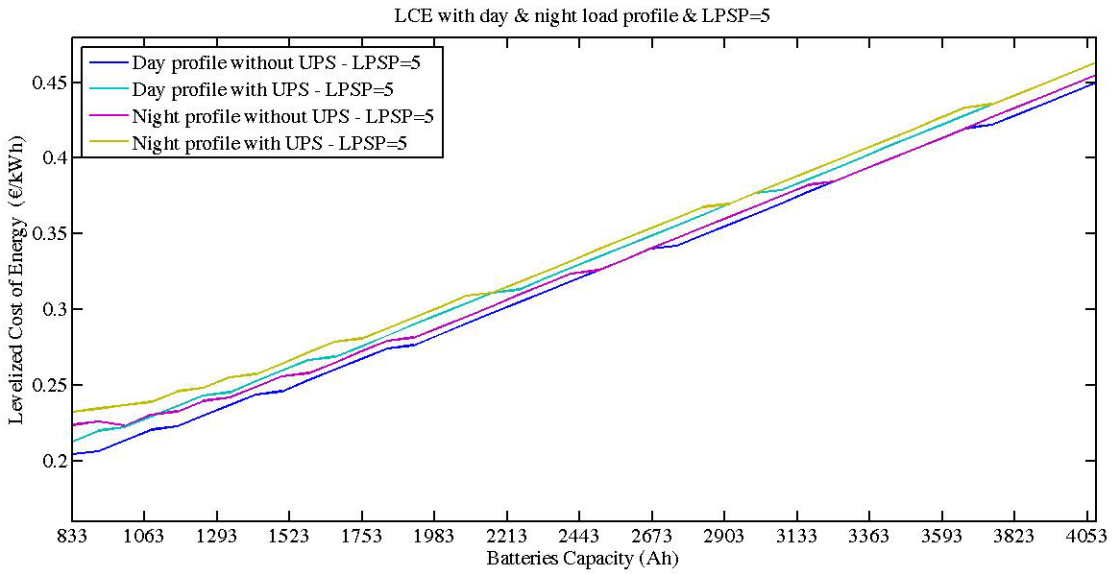


Figure 9-30 LCE is presented in this figure versus batteries capacity.

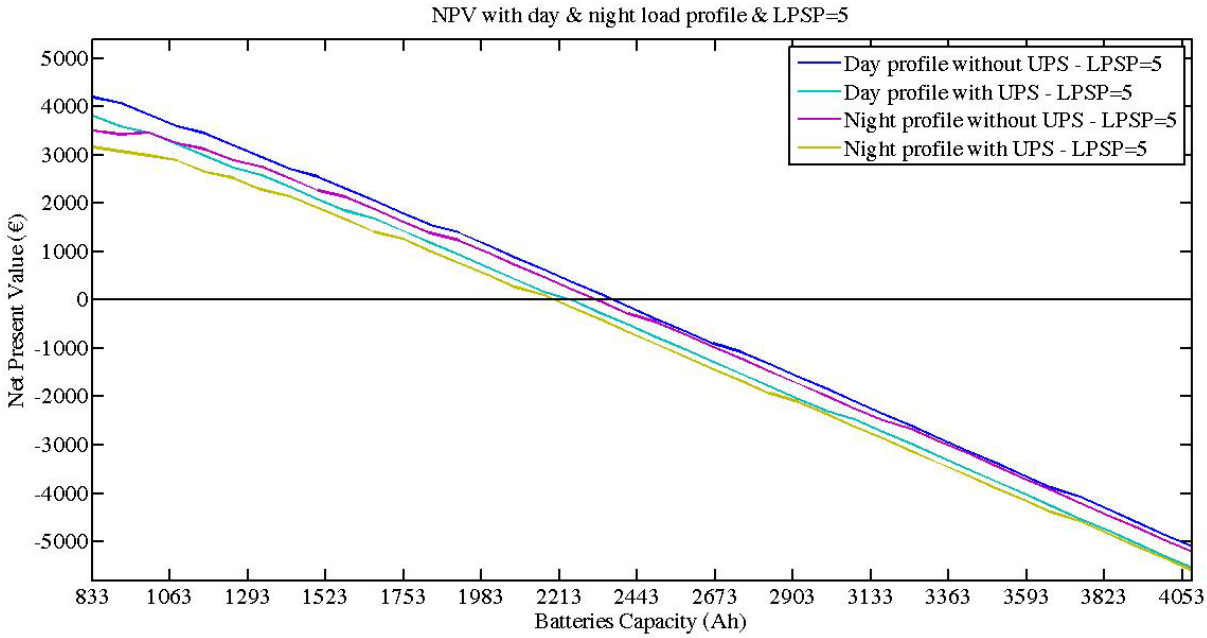


Figure 9-31 Net present value for the obtained systems with day and night load profiles for the two configurations, with LPSP=5%.

The PV power, at optimum configurations, is greater without UPS at day profile, but lesser when night is implemented (figure 9-28). Optimum system for the night profile is found with a batteries capacity of 1000Ah, while for all others were 833Ah. LCE is increased when UPS appears at the value of 4% for both profiles. The best net present value occurred for the case with day profile without UPS, and it is 4199€.

Table 9-7 In this table are presented the technical and economic parameters for the optimum systems per configuration (with and without UPS).

Configurations	PV Generator		Excess Energy		Battery Capacity (Ah)		LCE		NPV	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
UPS	2.52	3.08	37.11	43.64	833	833	0.2127	0.2323	3828,00	3163,00
Without UPS	2.66	2.8	37.23	38.37	833	1000	0.2041	0.2232	4199,00	3464,00

9.5.3 Evaluation of the system configuration with LPSP=10

In this part of the study are presented the size of the obtained PV generators and evaluated with economic indicators of LCE and NPV. Loss of power supply was set equal to 10 and the obtained systems are presented at figure 9-32.

The PV generators for the initial batteries capacity are reduced at least 28% related to the previous case with LPSP 5%. The resulting systems with the loss of power probability increased from 5% to 10% produced more than 25% less photovoltaic generator.

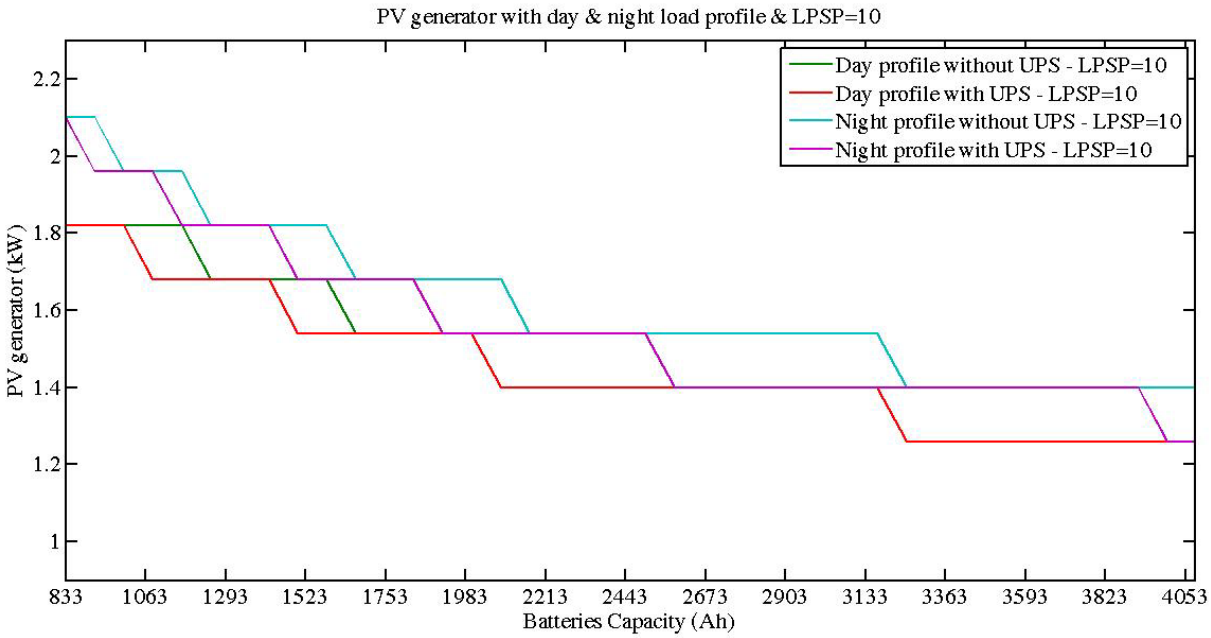


Figure 9-32 Here are presented the sizes for the systems occur at different capacities of the batteries for the two configurations and two load profiles.

The PV generators at the starting batteries capacity it was found equal for the two configurations for each load profile. Remarkable is the fact that the day-night profiles, for the formation without UPS, and for batteries capacity of 3250Ah or higher, produced the same generators of 1.4kW. Also, the systems with UPS produced lower PVs in almost half of the systems calculated for each load profile.

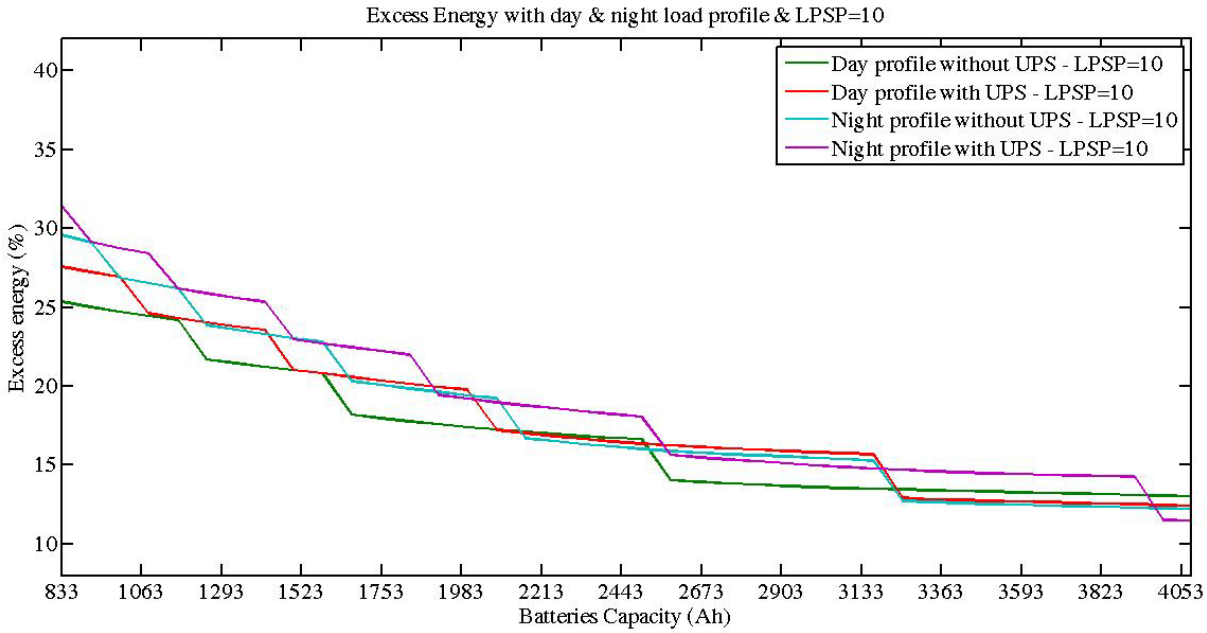


Figure 9-33 Energy burned to dumped loads when loads are satisfied and battery fully charged presented with much lower values at all cases with previous state and LPSP=5.

Next, at figure 9-33 the excess energy is depicted. Along all the obtained systems the fluctuation between the systems with or without UPS for each load profile is ranging from 0-2%, and those having UPS reaching the higher portions.

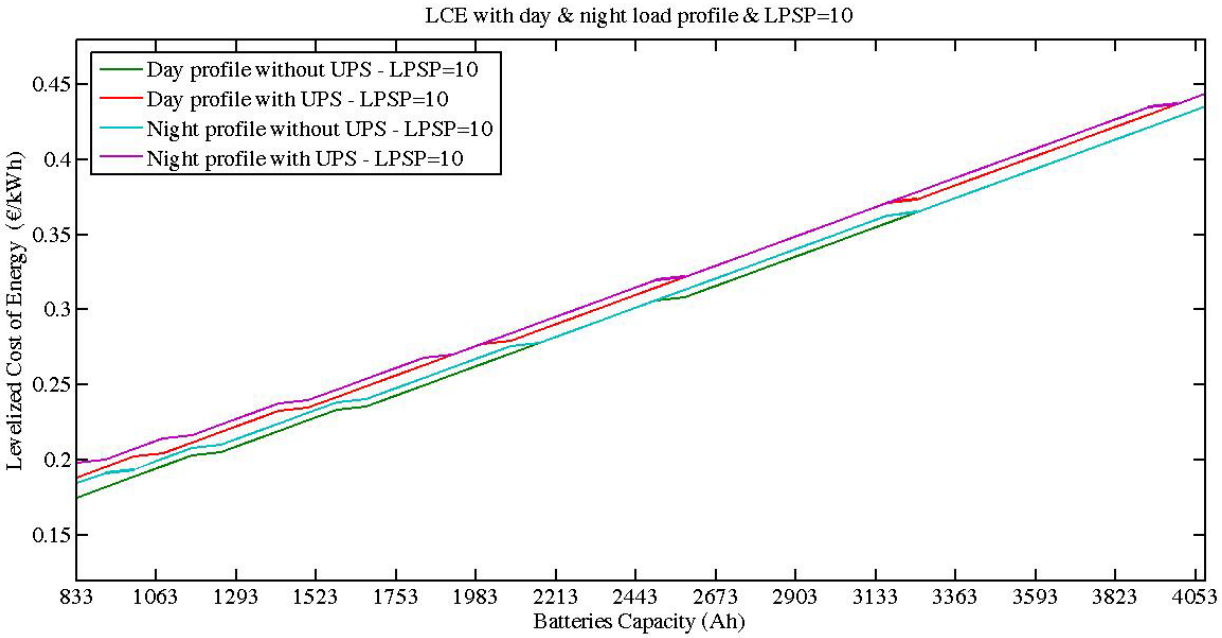


Figure 9-34 Levelized cost of energy is almost linearly increased in all cases.

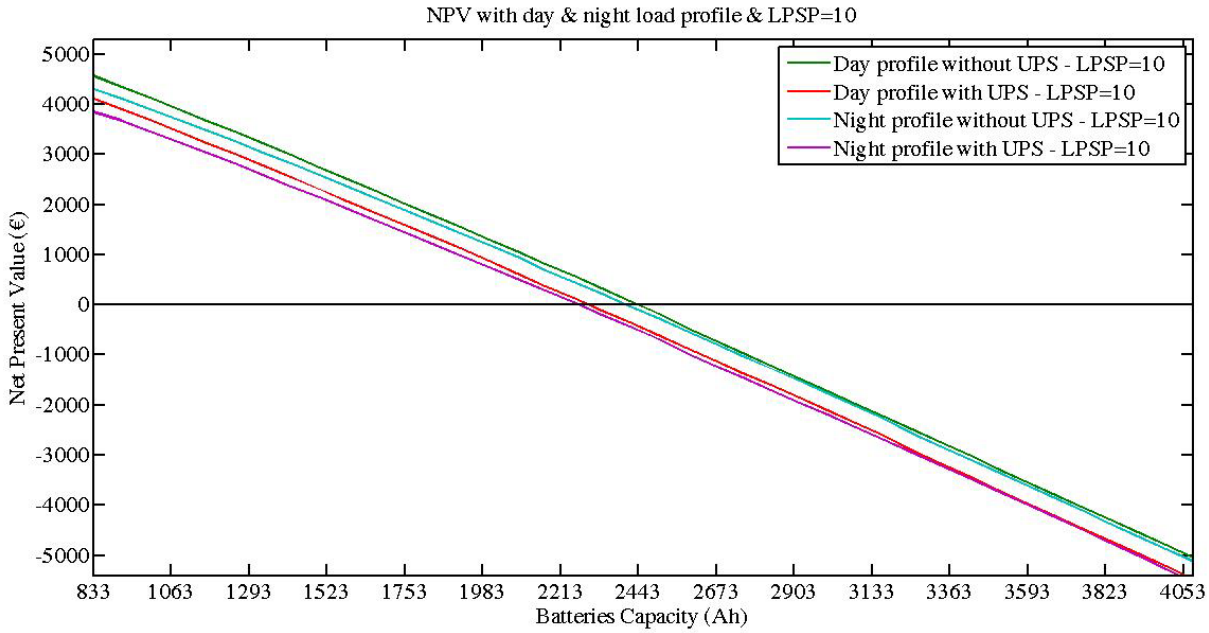


Figure 9-35 Net present value for the formations with and without UPS, and for the two load profiles day-night.

From figure 9-34 the systems produced with the day profiles are considered to be the most advantageous, under LCE factor. Net present value (figure 9-35) shows for the two formations always the one without UPS is the most cost effective solution for all the obtained systems per profile.

Day load profile it is dominant to the night one; generated energy comes from the PVs is greater than from WT, and then the whole system is affected from the time of the solar energy appears. Additionally, the contribution of load demand and production matching contributes to that.

At table 9-8, all the optimum systems were obtained with 833Ah batteries capacity. The most viable system was that without UPS and with day profile, which produced a LCE of 0.1747€/kWh and NPV of 4573€.

Table 9-8 In this table are presented the technical and economic parameters for the optimum systems per configuration (with and without UPS) per load profile (day-night).

Configurations	PV Generator		Excess Energy		Battery Capacity (Ah)		LCE		NPV	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
UPS	1.82	2.1	27.57	31.43	833	833	0.1882	0.198	4125,00	3853,00
Without UPS	1.82	2.1	25.35	29.59	833	833	0.1747	0.1845	4573,00	4306,00

10 CONCLUSIONS

At this thesis an analytic dynamic iterative approach is produced for the simulation of a hybrid energy system consisted of PV and WT generators and batteries as a storage bank. All simulations were conducted in hourly intervals under different load profiles, two different power evaluation criteria, LLP and LPSP, and for two different configurations with and without UPS. Optimum systems per case were calculated under the economic terms of LCE and NPV. After, this iterative approach with the configuration without UPS and LPSP equal to zero, it is compared with the graphical construction technique presented by Markvart T. The last one uses the monthly daily mean values of solar irradiance and wind speed and not considering of any storage system.

Appropriate time-series of meteorological data for solar irradiance, wind speed and ambient temperature were derived from the specified basis of Meteonorm in hourly intervals for the site of interest, Rhodos island, Greece. Next, the solar data converted to the angle of 36^{o} being similar with site's latitude and wind speed data translated to 23m at the hub-height of wind turbine, from the reference height of 10m. Continuing several load consumption profiles were used, which are daily, day, night and hourly-based weekly and all being 10kWh/day. For the purpose of sizing of a hybrid energy production system by renewable energy sources, it was produced an iterative simulation method by the help of a computing programming engine (MATLAB).

At the beginning a simulation is conducted with a loss of power supply probability (LPSP) equal to 5% between three systems constituted of only of photovoltaics (PVs), only of wind turbines (WTs), and a hybrid system with PVs and WT, and for all of them batteries were used as a storage bank. The results were evaluated with economic terms of levelized cost of energy (LCE) and net present value (NPV). The higher positive values for the NPV were obtained for hybrid systems and the best configuration it is found with a value of 3678€ considering all costs (installation, maintenance, replacement) for the systems life, which decided to be 25 years. For the simulation it is used the hourly-based weekly load profile.

Next comparison of the results are discussed. At the beginning a hybrid system was simulated with the proposed analytical dynamic iterative method by increasing the number of WTs till the number of 9 with a LPSP set at 0% and compared with the graphical approach, presented by Markvart. Iterative approach was conducted with a steady hourly load of 0.416kW/hr and the day profile. The graphical approach found to have a very small initial investment cost, but this oversimplified methodology doesn't account many parameters, like the rest of the system components, lifespan of the system and lifecycle of the components, installation and maintenance costs, storage system, variation of energy sources

production and load consumption in short intervals, and finally the economic benefits for the investor, they revealed a inapplicability in reality.

Then the two parameters of loss of load probability (LLP) and loss of power supply (LPSP) implemented for different values of losses 0%, 5% and 10% and it is figured out the effect on systems sizing. Simulation is done with the weekly load profile in hourly intervals. For the case of LPSP/LLP=0, fully autonomous system, the produced systems were identical but with negative NPV for the lifespan of the system. With the power criteria value being 5% the PV generators were essentially reduced. The optimum system was found for batteries being equal to 833Ah for both parameters, and the LPSP criterion provided a PV generator lower almost 19% and with higher net present value that equals to 841€. Thereafter, when the technical criteria set at 10% the gap between the two methods of the produced PVs was decreased at 12%. This differencing is due to the nature of the failures as LLP counts the times and LPSP the quantity of Watts didn't satisfied. Subsequently, the method with the LPSP is more reliable, because LLP it seems to slightly overestimate the size of the generators.

The study investigated also the effect of different load consumption profiles and different time intervals on the renewable energy system sizing, and the obtained results were of substantial importance. Particularly, for the daily load profile at the optimum case the PV generator was found constituted of 17 modules. The worst system it was derived with night profile which constituted of 23 PVs. The second profile with the lower number of PVs, after daily, was the day profile with a PV generator of 2.66kW_{peak} (19 modules). Resulting it is seen that smaller intervals definitely provide higher accuracy and therefore greater generators. Also, the matching of the produced energy with the consumption profile is another observation, and that's for day profile occurred with a lower system.

Finally, the results of two different configurations with and without uninterruptible power supply (UPS) with day and night load profiles and under various LPSPs were compared. An observation here is when night load profile is used higher PV generators occurred. Once LPSP was increased there was a convergence on the difference of the produced PV number of the two load profiles, for both configurations. UPS when used, produced at most systems lower peak power of the PVs. But as an aspect of economic efficiency all the systems without UPS provided better values of LCE and NPV for both load profiles and all the LPSPs (0%, 5% and 10%). Therefore, even if the calculated systems were smaller with UPS the cost during system lifespan was economical not the best, because of the additional costs of the UPS to the total of the system.

Concluding it is necessary for the optimum sizing all these parameters studied in this project to be taken into account. Firstly, the choice of a convenient method is necessary, which examines as much as possible parameters effecting the system being under evaluation. Hourly intervals or even less provide a better view of the production and consumption energies matching. They highlight the

times at which an actual installation may fail, if not taken into account, more precisely. Thus, the obtained system exploits the produced energy even better and the possibility of under- or upper- estimation of the system is reduced drastically. Crucial for the process of sizing is the accuracy of meteorological data and the period of time-series. Short period of time data might lead to wrong estimations, and system failures. Also knowledge of the occupant energy behavior is essential for the right choice of system components.

In order the estimated system to be more efficient for the investor energy saving interventions must be proposed and classified in two basic categories, passive and active. Passive refers to the strategies of constructing or renovating buildings with lower energy demands for lighting and heating. Active mostly acts to the energy habits of the people or unawareness. Informing about the usage of the appliances and even adaptation of systems for energy management could also reduce the peak power of the generators to be installed. It is astonishing the fact that if only transposing the working time of some appliances it could react in a reduction of the system [124] or the energy that is added from the grid utility provider.

This thesis provides a total of a broad scope for evaluation and implementation of a hybrid energy PV-wind system, and stresses the responsibility of the designer engineer that must exhibit by adjusting RES technologies on a building construction, aiming both the energy and the economic benefit of the investor.

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