MATHEMATICAL SIMULATION AND OPTIMIZATION OF A STAND ALONE ZERO EMISSIONS HYBRID SYSTEM BASED ON RENEWABLE ENERGY SOURCES

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ABSTRACT

Renewable Energy Sources (RES) are the most promising resources of energy production for everyday life. Therefore, the precise combination of RES based technologies into hybrid systems could provide the solution to several energy problems facing the planet. The motivation of the present research study is the total understanding of the prevailing phenomena by using RES equipment in several projects.

Initially the basic RES based technologies will be described together with the main fundamental physics on which their operation is based on. Power plants that are supplied with "green" energy and are connected to national grid will also be described. This thesis will then focus on their evolution; that is stand alone hybrid RES based systems. By presenting the RES systems the necessity of buffering systems will become apparent as the most crucial parts of off-grid systems. Therefore, the most well-established buffering technologies will be analytically presented in order to be subsequently embodied into the simulated RES applications.

Following the above theoretical approach of RES based equipment and hybrid systems in general, this thesis will focus on a more applied research study comprising the energetic and economical simulation and optimization of a RES based stand alone system that is already installed in Leicestershire, UK. Based on local meteorological data, an optimization strategy has been developed to identify the most economical and efficient scenarios for electricity generation to cover the desirable load on an annual basis. Furthermore, the environmentally-friendly character of the system was highly concerned with emissions reduction; therefore the capability of an off-grid system was also investigated. The feasibility of RES based systems for electricity supply will then be presented for four different Greek Islands. Three specific typical loads have been selected to be covered and the grid connection was considered optional. Up to this point the simulation and optimization procedures were applied by using the HOMER software tool in order to investigate the most suitable well-established platform in the world.

After the theoretical research study on the most well-known platform of HOMER an innovative optimization theory based on the energy part of a hybrid system will be presented in order to

select the most efficient system according to the desired requirements and the location of a RES based project.

This thesis will then focus on the design and operation of an autonomous hybrid system under real-life meteorological conditions which is capable of simulating several loads assumed to cover the electricity demands of small buildings. The specific hybrid system embodies technologies that use photovoltaic and wind energy in combination with an electrochemical storage bank. Experiments on the coverage of annual loads regarding a typical house, a typical country house and a small company were also performed to prove the feasibility of the stand-alone system. The same established RES project was then simulated on a yearly basis using the HOMER software platform to determine real-time results. The above analysis revealed that HOMER software cannot successfully simulate the operation of such a system, therefore the design of a new mathematical model to produce results similar to those of the experimental process was considered essential.

Renewable Energy Sources are characterized by their unpredictable behavior, since their availability depends on local meteorological conditions. Therefore, the use of intermediate energy storage (buffering) is essential for an uninterrupted energy supply, especially for off-grid stand-alone systems. For this reason, at the end of this thesis the design and construction of a flywheel energy storage system (FESS) is presented in order to prove if this system could be incorporated into an RES system in a real-life scenario, thus strengthening the eco-friendly character of such a project and eliminating the drawbacks of existing storage technologies.

CONTENTS

FIGURES AND TABLES

1 INTRODUCTION

In this chapter the necessity of Renewable Energy Sources (RES) in everyday life and the main advantages of their usage will be outlined. The known issues arising from the integration of RES based technologies into a hybrid system will then be described. Finally, the principal objective and motivation of the research will be defined. This chapter will conclude with a brief overview of the organization of this thesis.

1.1 CURRENT STATUS

Energy is important for covering the needs of populations in developed and developing countries. Using an energy source for electricity production is essential for the welfare of households and generally for human life. Electricity production currently depends mainly on conventional fossil fuels, which are characterized by pollutant emissions during their use. Therefore, improving access to modern renewables is an important target for each country towards its development.

During the last two decades, the energy sector has changed significantly. Fossil fuel deposits have been reduced by continuously increased consumption to cover population needs. Additionally, their acquisition costs have increased. The efficiency of conventional fossil energy sources during energy production is not high enough to overcome their pollutant character. Thus, the attention of many countries has shifted to the development of renewable energy options. In Europe, several factors contribute to the demand for a more eco-friendly electrification than in the past. The European Union has decided to follow a common line to reach a specific target with positive consequences on climate and human health by the year 2020, as follows (see: http://epp.eurostat.ec.europa.eu):

- Greenhouse gas emissions should be reduced by 20% compared to 1990.
- The portion of Renewable Energy Sources in final energy consumption should be increased to 20%.
- Energy efficiency in RES should improve by 20%.

Each European Union country has been set a specific target for the above three aims, however, it has only reported on the first. Figure 1.1 shows the progress of greenhouse gas emissions in Greece, compared to the European mean, where 1990 has been set as the reference year.

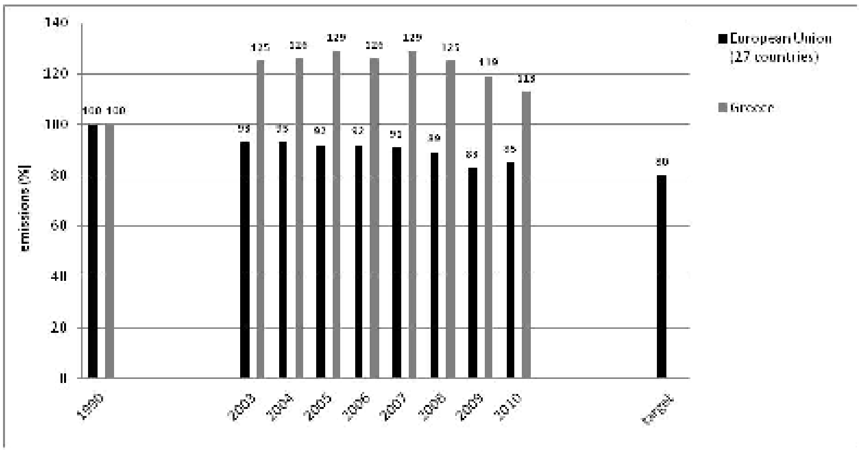


Figure 1.1 Greenhouse emissions in Greece compared to the European mean.

Figure 1.2 presents the increasing percentage of renewable sources in the European Union towards the 2020 target. The figure also shows, the percentage of RES obtained in Greece during the same period. Similar targets have been set for each of the 27 European countries under a very tough deadline beyond which financial penalties will be imposed.

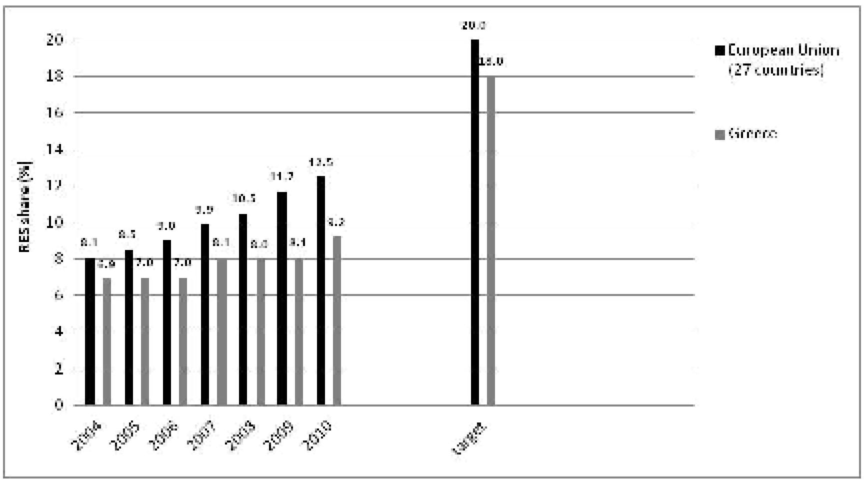


Figure 1.2 RES share in Greece compared to the European mean.

Finally, Figure 1.3 presents energy efficiency and shows the percentage of energy savings of fossil fuels in Tones of Oil Equivalent (TOE) units. A reduction to below 100% through the years, as shown in Figure 1.3, reveals that less fossil fuels are used for energy production and that these fuels are progressively being replaced by RES based energy systems.

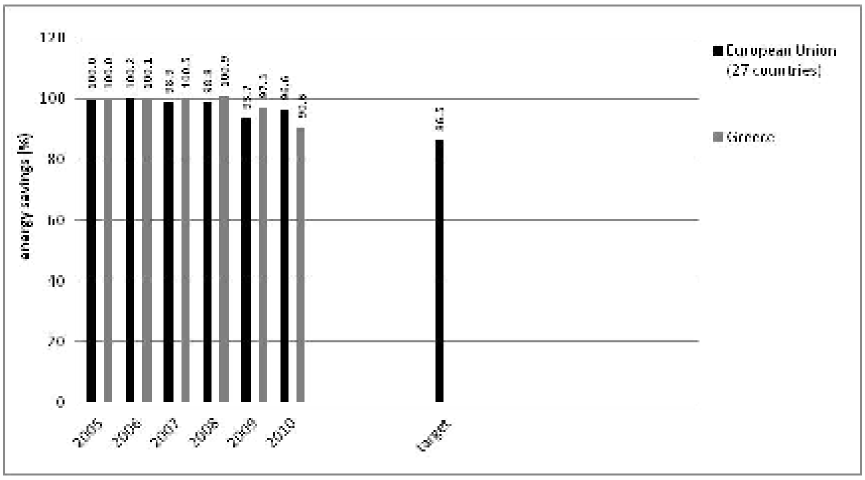


Figure 1.3 Energy savings in Greece compared to the European mean.

This turn to RES based systems for electricity production is quite slow, despite the existence of numerous scientific studies that show quite the contrary (http://epp.eurostat.ec.europa.eu).

1.2 PROBLEMS CAUSED BY WIDESPREAD USE OF CONVENTIONAL ENERGY SOURCES

Further to the targets set by EU, high interest in RESs seems to be a global phenomenon with different characteristics per specific case.

1) The recent increases in fossil fuel prices in combination with the limited extension of national grids.

In Africa the current interest on renewable energy is driven by increased oil prices, made more evident by the fact that earnings from the exchange value of Africa's currencies are very low due to world market prices. Petroleum imports as a percentage of income by exports has almost doubled during the last decade for the majority of African countries (Karekezi, 2002). The second most important development that increases interest in renewables in Africa is the crisis faced by most power utilities in several countries due to limited extension of the national grid which is affected by the territorial and climatic characteristics of the region, as well as by politics. These countries face power supply limitations which consequently affect their economies (Karekezi, 2002).

2) The limited deposits of fossil fuels.

Asia has been facing a power crisis for almost a decade. The power generation capacity cannot meet the demands of the population for electrification, thus only 20% of the total population is connected to the grid (Hossain & Badr, 2007). Only 25% of this population resides in urban areas and 10% in rural areas (Hossain & Badr, 2007). Deposits of natural gas, which is the main commercial primary energy source, are limited. Asian economies are not strong enough to sustain large fossil fuel imports and at the same time the evolution of RES projects in Asian countries is stationary, mainly due to political choices (Hossain & Badr, 2007).

To satisfy consumer demand, national investments have been made on large-scale RES based projects that support the existing grid, such as hydropower or biomass applications. Although hydropower applications remain by far the most important of the renewables for electrical power production worldwide, they can only be established near rivers or lakes with sufficient water (Paish, 2002, Nfah & Ngundam, 2012). Similar difficulties are faced for the use of biomass as an energy source as the installations occupy large areas of land thus prohibiting domestic use. Moreover, in order to provide continuous and safe allocation of the produced power to each individual consumer, the development of a grid is crucial in cases where production is centralized due to technological or other reasons. For instance, when coal is used to produce electricity, it is obvious that a connection path (grid) is necessary to transport the energy from the production point to each consumer. Furthermore, the centralized transport of electrical energy allows political forces that have access to and control the grid, to obtain higher political power through threats about supplying power or not and the ability to exclusively define pricing policy.

1.3 MOTIVATION AND RESEARCH SCOPE

Fortunately, RES do not have such limitations, as they are presented above, since electricity can be produced by the individual consumer and in-situ, i.e. in the same place where consumption occurs. It is important to note that a solution where any consumer would independently cover his own energy requirements by producing electricity locally using RES based systems does not appear feasible, because of the inevitable gap between production and consumption rates. This gap is observed due to the stochastic dependence of RES based productivity on local meteorological conditions.

One solution to the efficient management of energy excesses and requirements could be found in the use of smart micro-grids. A micro-grid is an energy logistics system based on the concept of “community”, and whose members are both energy producers and energy consumers. Each consumer provides their excess energy to the community and, in turn, the community provides the amounts of electricity required to cover each consumer’s energy demands when necessary. This distributed production scheme by-passes the national grid, thus avoiding the installation, maintenance and operating costs of such a system. At the same time, the political factor can be excluded from the process of energy production and provision.

Another solution is the evolution of small-scale domestic RES projects which should be promoted by governments worldwide to encourage individuals to use RES to cover their power requirements. These applications can be supported by the use of solar and wind energy in combination with mature buffering technologies for micro-grid optimization. One of the advantages offered by renewable energy technologies is their potential to provide electricity in areas not served by national power grids. This prospect leads to RES based, hybrid, autonomous systems.

Research questions - With this in mind this thesis will address the following questions:

- How can weather conditions change the behavior of a hybrid system and to what extent?

- How important is the correct choice of RES-equipment according to the primary desirable electricity requirements that should be covered by the established system?
- Can an RES based, stand-alone, hybrid system be feasible and under which circumstances?
- How accurate is the prediction of the operational results of such a system when using existing and innovative software simulation tools?
- How can be the eco-friendly character of such a system be reinforced and what are the main weaknesses during their operation?

This thesis focuses on answering the above questions regarding the involvement of RESs in everyday life. Moreover, this study could help provide solutions to such problems as supplying electricity to remote areas, which usually requires large investments and leads to power losses associated with transmission and distribution networks.

1.4 ORGANISATION OF THESIS

This thesis adopts theoretical and experimental analysis of different small-scale hybrid systems in order to prove under which circumstances such systems can be feasible and how their operation can be predicted by using different simulation tools thus protecting a future investor from wasting large sums of money.

Chapter 1 provides a general introduction of this thesis, including the principal objective and research focus, while the rest of the research work is split into five parts. Part A of this thesis provides an overview of the general theory of RES technologies and hybrid systems based on the relevant available literature (Chapter 2). Part B presents several simulated hybrid systems (Chapter 3). Specifically, an already established RES based on-grid system is simulated and optimized in order to prove that following a thorough study of local meteorological data and existing RES technologies, this can be transformed into a feasible stand-alone and totally eco-friendly stationary application. The same simulation and optimization technique was also used for several hybrid applications in Greece. Part C investigates an innovative optimization theory (Chapter 4) and a new software simulation tool is designed from scratch to cover the grey areas of existing simulation tools (Chapter 5). Part D focuses on innovative buffering technologies that have more eco-friendly characteristics than those already available in the global market (Chapter 6). Finally, Part E contains the conclusions (Chapter 7) and future research proposals (Chapter 8) that arose from both the literature review and the empirical-experimental research.

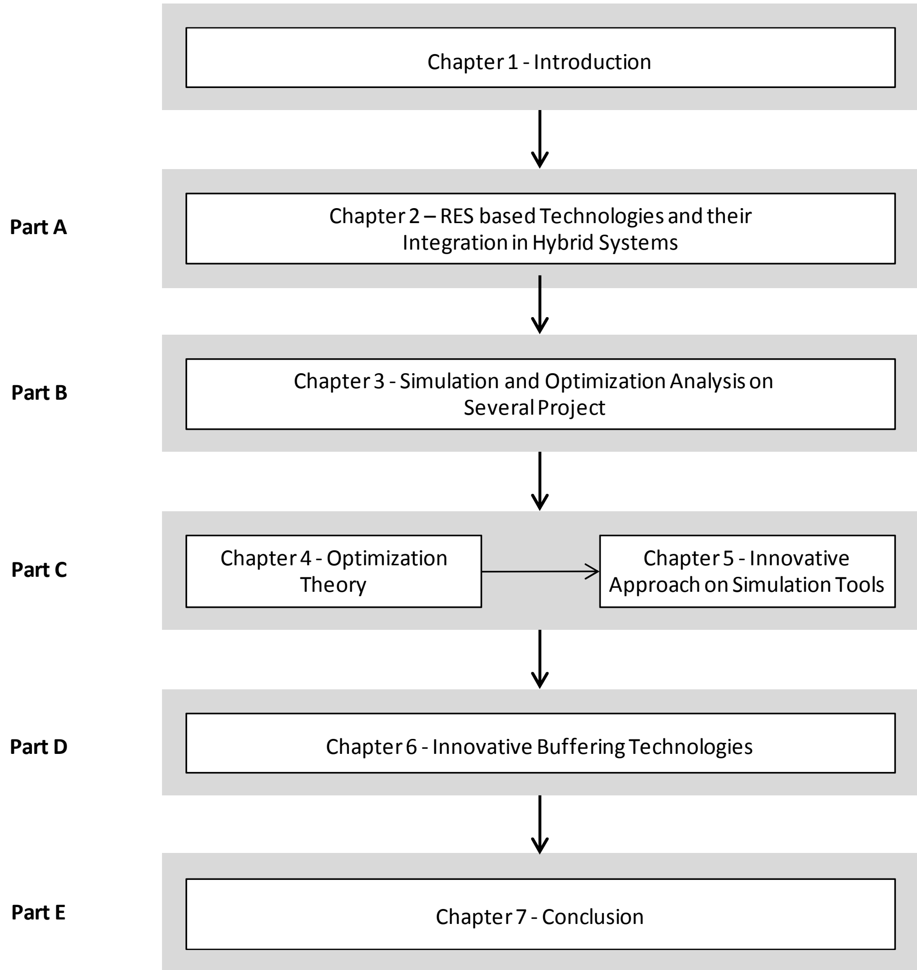


Figure 1.4 Thesis organization.

To summarize Chapter 1, this thesis investigates the simulation and optimization of hybrid, RES based stand-alone systems from an investor's point of view.

The main aim is to decode the combination of RES technologies in order for them to be embodied into a hybrid system, to be proved the energy and financial feasibility of several simulated project based on existing software simulation tools, to discover the grey areas in the operation of such systems using the theoretical analysis based on existing software, and finally to propose innovative tools to predict each system's operation, and buffering technologies for a totally eco-friendly, zero-emission system.

Box 1 Summary of thesis introduction.

2 RES BASED TECHNOLOGIES AND THEIR INTEGRATION INTO HYBRID SYSTEMS

The first section of this chapter describes basic RES based technologies and the main fundamental physics on which their operation is based. Secondly, is presented a description of power plants that are supplied with “green” energy and are connected to the national grid, followed by their next evolutionary stage i.e., stand-alone hybrid RES based systems. Finally, from the presentation of several RES systems, the necessity of buffering systems becomes clear as these are the most crucial parts of an off-grid establishment. Here, the most well-established buffering systems will be presented and included in several simulated RES applications.

2.1 PERFORMANCE THEORY ON RES-BASED TECHNOLOGIES

Over the last 20 years, the world’s population has increased by approx. 1.6 billion people and it is expected to rise by 1.4 billion over the next 20 years (REN21, 2011). The above trend corresponds to an analogous increment in electricity demands due to industrialization, urbanization and motorization that are strongly associated with increased energy consumption, which consequently affects the fossil fuel process. In addition, the wasteful use of fossil fuels aggravates climate change due to continuous environmental pollution. Therefore, the use of RES, which are usually characterized by efficient energy conversion cycles, is further strengthened.

The use of alternative energy sources that are not dependent on fossil fuels seems to be an option, and renewable energy technologies have thus begun to play an important role in the energy market. Figure 2.1 shows the proportion of renewable sources in global electricity production for the year 2010 as approximately 16%, and this figure increases constantly (REN21, 2011). Figure 2.1 reveals that the largest amount of green energy is produced by hydroelectric establishments.

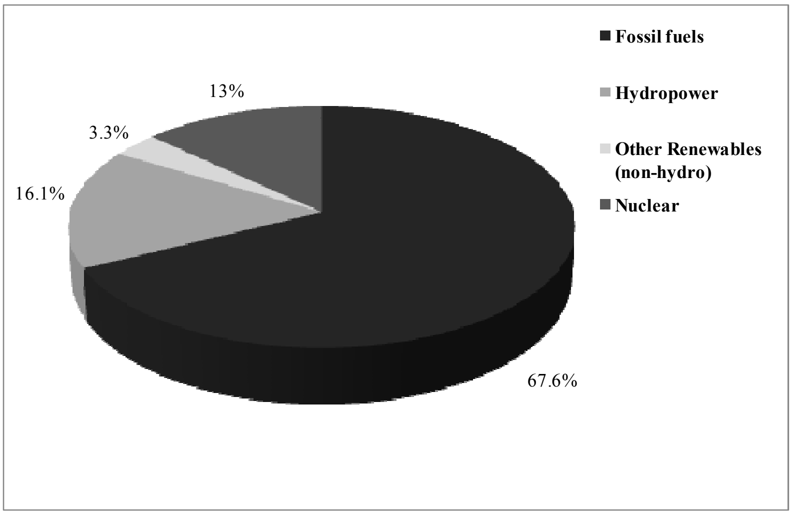


Figure 2.1 Distributions of energy sources in 2010.

Other eco-friendly technologies appear to be at an early stage of development as they represent only a small percentage in the global market. Fossil fuels and nuclear power both contribute 80.6% to global electricity production; however the reduction of their use is a social requirement as they raise serious safety and pollution issues. For this reason during the last decades, renewable technologies such as photovoltaic panels/arrays (PVs) and wind turbines have become popular and this is clearly shown in Figure 2.2 which depicts the increased worldwide use of such technologies (REN21, 2011).

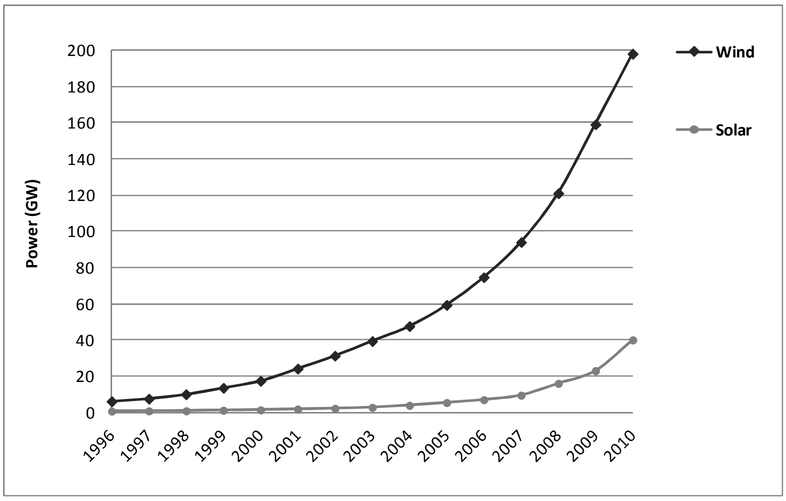


Figure 2.2 The increased use of wind and solar technologies over time.

In this part of the thesis it is considered essential to analytically present the basic fundamental physics on which technologies that take advantage of alternative energy sources are based on. All existing simulation tools embody this theoretical approach in order to prove if a specific location is suitable for a RES based system to be established, according to the dominant weather conditions. At the same time the performance of such a system can be predicted by these simulations without the risk of losing investment costs.

Hydropower - Hydroelectricity is one of the most mature forms of renewable energy (Paish, 2002). The electrical energy which can be produced by a hydroelectric unit depends on the control of the flow of the water. This factor is the most important because the spin of the turbine depends on that flow (water potential) (Tsikis & Coutelieris, 2009), so the kinetic energy of water is transformed into mechanical and finally, into electricity through the capacitors. The expression which represents the above procedure is Equation 2.1 (Foss, 1998):

$$P_{hydro} = \eta_{turb} \cdot \eta_{gen} \cdot \rho \cdot g \cdot h_{eff} \cdot Q \ ,$$

where η_{turb} and η_{gen} is the efficiency factor (%) of the turbine and the generator respectively, ρ is the density (kg/m^3), g is the gravitational acceleration (m/s^2), h_{eff} is the effective head (m), and Q is the volumetric flow rate (m^3/s).

Equation 2.1 The transformation of water kinetic energy into electrical energy.

The use of hydropower technologies is characterized by specific restrictions due to their strong local character because such systems can only be built in specific sites near lakes or rivers. Moreover, such a construction requires high initial costs and massive machinery with significant environmental impact (Sims, 1991).

Wind power - Wind technologies for electricity production is the second most well-established form of "green" equipment. The amount kinetic energy that can be captured by wind turbines and converted to electrical power depends on the wind speed (wind potential) and the height of the wind turbine, since wind speed varies with height following the Weibull distribution (Tsikis & Coutelieris, 2009). The energy stored in the wind potential can be expressed through Equation 2.2 (Lilienthal et al., 2004, Tsikis & Coutelieris, 2009).

$$E_{kinetic} = 0.5 \cdot m \cdot u^2,$$

where m is the air mass (kg) and u is the wind speed (m/sec) in real-time conditions.

Equation 2.2 The energy stored in wind potential.

By using the mass flow-rate instead of the mass, wind power can be obtained through Equation 2.3 (Manwell et al., 2002). The critical parameter for the produced electric power through the blowing wind is the size of the blowing area, which is represented by the rotor swept area of the wind turbine.

$$P_{wind} = 0.5 \cdot A^2 \cdot 1.23 \cdot u^3,$$

where A is the surface area (m^2) and u is the wind speed (m/s).

Equation 2.3 Calculation of the mechanical power of a typical wind turbine.

Moreover it must be noted that in the case of horizontal axis turbines, approximately only 30-40% of the wind power in Equation 2.3 can be transformed into electrical energy because of the mechanical losses of the construction (Manwell et al., 2002). This percentage is not an arbitrary parameter but is related to the power coefficient which is unique for each single wind turbine and is given by the manufacturers. Another crucial factor is air density which will be considered as constant for the simulated projects of this thesis, despite the fact that it varies with height, because the altitudes of the projects' locations are not high.

Solar power - The structure and characteristics of the sun determine the nature of the solar energy transmitted to earth. Photovoltaic panels (PV) constitute the technological achievements that take advantage of the energy in solar radiation and transform it into DC load. The electric power produced by a typical photovoltaic array is given by Equation 2.4 (Duffie & Beckman 1980, Kolhe et al. 2003).

$$P_{solar} = P_{STC} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{STC}} \right) \left[1 + a_P \left(T_C - T_{C,STC} \right) \right],$$

where P_{STC} is the output power of the panels in standard test conditions, f_{PV} is the derating factor, $\overline{G}_T$ (W/m^2) is the solar radiation incident, and $\overline{G}_{STC}$ (W/m^2) is the radiation in standard test conditions (1000 W/m^2). The last bracket which contains the temperature coefficient $a_P \left(\frac{\%}{^oC} \right)$ represents the performance of the PV cells which is influenced by the temperature, T_C (^oC), to which the photovoltaic array is exposed in real-time.

Equation 2.4 Power produced by a typical photovoltaic panel.

The critical parameters for the conversion of solar energy into electricity are f_{PV}, T_C, and the orientation factor which is covered in the numeration $\overline{G}_T$ of the ratio of solar radiation as shown in the first parenthesis in Equation 2.4. It is clear that all these factors comprise the input variables of a typical solar system. Moreover, they are considered as constants for a specific location of the photovoltaic arrangement. The orientation of the photovoltaic panels, β, which is hidden in the numerator of the parenthesis of Equation 2.4, is used in the next expression through which the solar radiation incident on the photovoltaic array is calculated (Duffie & Beckman 1980).

$$\overline{G}_T = \left(\overline{G}_b + \overline{G}_d A_i \right) R_b + \overline{G}_d \left(1 - A_i \right) \left(\frac{1 + \cos\beta}{2} \right) \left[1 + f_{PV} \sin^3 \left(\frac{\beta}{2} \right) \right] + \overline{G} r_g \left(\frac{1 - \cos\beta}{2} \right),$$

where $\overline{G}_b$ and $\overline{G}_d$ are the beam radiation of the incident and the diffuse radiation correspondingly, A_i is the anisotropy index of the solar radiation, r_g is the ground reflectance, and β is the angular orientation of the PV panels.

Equation 2.5 The calculation of the solar radiation incident.

As shown by the above expressions, all the above factors determine the final power output of the established panels. More precisely, the incline at which the panels must be positioned is one of the most important parameters for the correct simulation of a system based on photovoltaic arrays.

2.2 Basic Financial Theory on RES Based Projects

The performance analysis of a system to cover the desirable load alone is nowadays insufficient for its selection. Economical issues are crucial when making the final choice of the combination of components during the design of a unit.

2.2.1 Theory on Net Present Cost Calculation

The initial and operational costs of a RES based system are high and constitute one of the most crucial parameters for the design of the system. Therefore, it is necessary to calculate the Net Present Cost (NPC), which roughly estimates the amount of money which must be spent throughout the lifetime of the project in years, and is given by Equation 2.6 (Brealy & Myers 1991).

$$C_{NPC} = \frac{C_{tot}}{CRF},$$

where C_{tot} is the total cost (€) of the establishment and CRF is the Capital Recovery Factor.

Equation 2.6 The calculation of the NPC of a system.

The capital recovery factor is given by Brealy & Myers at (1991) through Equation 2.7.

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1},$$

where i is the real interest rate and **N** is the lifetime of the project in years.

Equation 2.7 Calculation of the Capital Recovery Factor.

Finally, the real interest rate can be calculated by Equation 2.8 (Brealy & Myers 1991).

$$i = \frac{i' - f}{1 + f},$$

where i' is the nominal interest rate and f is the annual inflation rate.

Equation 2.8 Calculation of the real interest rate.

For the numerator in Equation 2.6, the total annual cost of a system is the sum of total replacement, operational and maintenance costs and the salvage value of each component. The replacement costs are different for each component and are given by Equation 2.9 (Brealy & Myers, 1991).

$$C_{arep.} = C_{totrep.} f_{rep.} SFF\left(i, N_{comp.}\right) - S \ SFF\left(i, N_{proj.}\right),$$

where $C_{arep.}$ are the annual replacement costs, $C_{totrep.}$ denotes the total replacement costs for each component at the end of its lifetime, $N_{comp.}$ and $N_{proj.}$ is the lifetime in years of each component and the whole project respectively, S is the salvage value of each component at the end of its lifetime, and SFF is the sinking factor which will be analytically defined below.

Equation 2.9 The annual replacement cost for each device.

The second term of Equation 2.9 cannot be equal to zero because of the existing salvage value of some components at the end of the project's lifetime, and can therefore be given by Equation 2.10 (Brealy & Myers, 1991):

$$S = C_{tot.rep.} \frac{N_{rem.comp.}}{N_{comp.}} SFF(i, N_{proj.}),$$

where $N_{rem.comp.}$ is the remaining life in years of each component and SFF is the sinking factor.

Equation 2.10 The salvage value for each component at the end of a project's lifetime.

Finally, the sinking factor SFF, is a ratio which is used to show the future value of cash flows and is calculated by Equation 2.11 (Brealy & Myers, 1991):

$$SFF\left(i, N_{comp.}\right) = \frac{i}{\left(1+i\right)^{N_{comp.}} - 1}$$

Equation 2.11 The sinking factor.

2.2.2 BASIC THEORY ON DEPRECIATION COSTS WITH AN INNOVATIVE ADDITION

Another aspect of the financial analysis will be revealed based on the depreciation of the capital costs of a system through the years. Initially, the years for depreciation will be estimated for a stand-alone system using Equation 2.12 (Brealy & Myers, 1991):

$$Y = \frac{C_{cap.} - C_{gridcap.}}{C_{ygrid} - C_{oper.}}$$

where $C_{cap.}$ is the capital cost of RES components, $C_{gridcap.}$ is the grid connection capital cost, C_{ygrid} is the annual cost for the usage of the grid, and $C_{oper.}$ is the operational cost of a stand-alone system.

Equation 2.12 Cost depreciation in years.

The above calculation can be transformed by selling the excess electricity to the grid. Therefore, by including the sale profit, Equation 2.12 can be re-written as Equation 2.13 (Brealy & Myers, 1991).

$$Y = \frac{C_{cap.} - C_{gridcap.}}{C_{ygrid} - \left(C_{oper.} - E_{excess} M\right)}$$

where E_{excess} (kWh) is the excess electrical load produced by the RES and sold to grid, while M (€/kWh) characterizes the sell price as fixed by the Greek Power Company according to the Greek law for established projects.

Equation 2.13 Cost depreciation in years when selling energy back to the grid.

The innovation introduced here is the cost of emissions that must be paid for by the National Power Company because of their use of coal. Although through the Kyoto protocol is going to be determined a specific price per emitted ton of CO_2 and this cost is considered constant for the simulated projects of this thesis. From the emissions of CO_2 per MW supplied by the grid, the price for the use of grid is increased and can be calculated by Equation 2.14:

$$C_{emissions} = E_{desload}\, Emissions\, C_{perton},$$

where $C_{emissions}$ is the total cost of the produced emissions if the desirable load was covered by the grid, $E_{desload}$ is the load which is appropriate for the constant operation of the established unit, $Emissions$ are the pollutant elements of the grid in tons, and C_{perton} is the cost of emissions per ton.

Equation 2.14 Cost of the emissions.

As hybrid systems do not use diesel or LPG generators as alternative sources, the operating costs given by Equations 2.12 & 2.13 are equal to annualized replacement costs.

2.3 RES Based Hybrid Power Plants

During the last decades considerable effort has been dedicated to developing hybrid energy systems. These systems utilize renewable energy sources such as wind, solar and hydro in order to produce "green" energy to cover a population's electrical needs. Hybrid systems are separated into two categories according to their integrated power management strategy, which can either support a grid-connection mode or an off-grid operation.

2.3.1 On-Grid Hybrid RES Based Systems

Due to the rising cost of fossil fuels coupled with the harmful effects on the environment caused by their use, many countries embarked on utilization of renewable sources of energy such as wind and solar, with the exception of hydro which is characterized by serious restrictions on its establishment as mentioned in the previous section.

Although the present research does not focus on large-scale on-grid RES systems established by several governments to support the national grid, it is essential to briefly present such projects in order to show the initial steps for the inclusion and promotion of renewable sources in everyday life. Wind is the world's fastest growing energy source with an increasing installed generating capacity in the last decade (Shaahid, 2011). Huge wind farms based on WECS (Wind Energy Conversion Systems) have been established all around the world and especially in countries with increased wind potential (with average wind speeds in the range of 3-8 m/s)

(Bellarmine & Joe, 1996, Petersen & Madsen, 2004). As Figures 2.3(a) and 2.3(b) present, the basic idea of such expansive wind farms is to produce an AC or DC electric load and then, through a control unit equipped with regulators or inverters, respectively, to supply this AC load to the national grid (Shaahid, 2011).

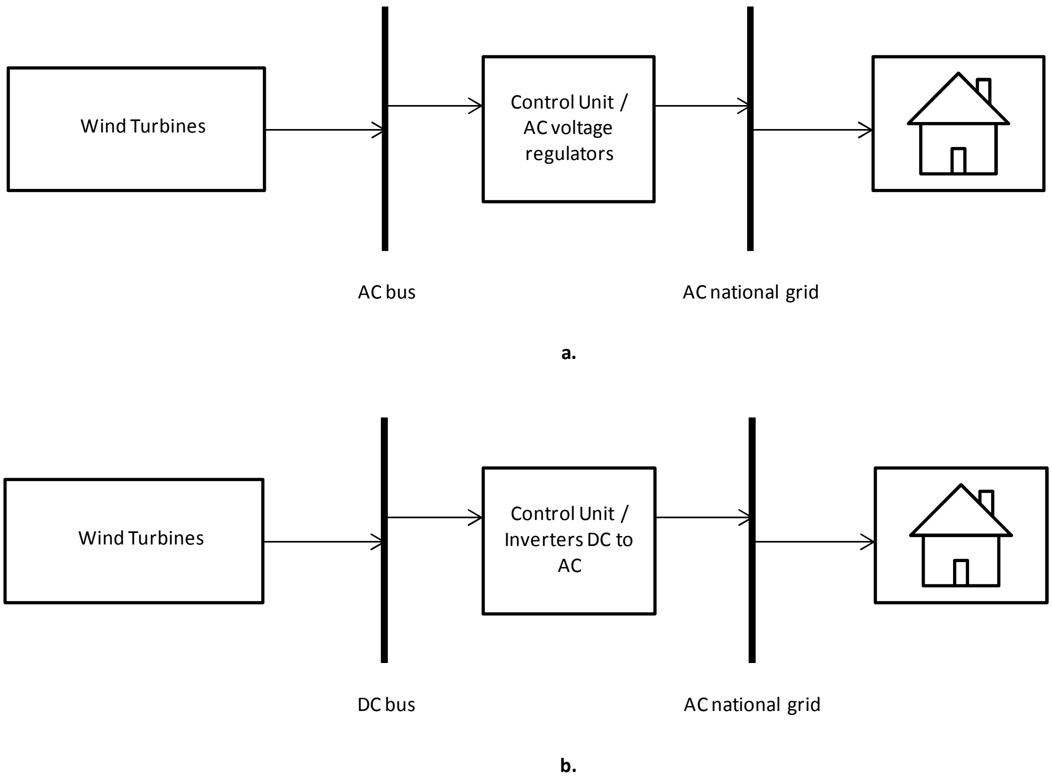


Figure 2.3 (a) Connection of an AC load wind farm to the national grid, (b) Connection of a DC load wind farm to the national grid.

Solar is the world's second fastest growing energy source with an installed capacity of PV systems that reached more than 6,500 MW peak by the end of 2006. Governments of the most developed countries, like United States, Japan and Germany, are leading the race in photovoltaic power development (Shaahid, 2011). The beginning of this trend was marked by the establishment of enormous photovoltaic parks that take advantage of solar energy. The establishment of a solar PV park follows similar basic principles as those presented in Figure 2.3 (b) for wind farms.

As cost minimization is the major driving force for any investment, the main global idea is to develop these technologies as small-scale individual RES based projects. These projects are on-grid systems which are designed to use power from the grid and the renewable technologies offer supplementary power during the day when the peak load is not so high. All producers have the opportunity to provide their energy to the grid while all consumers can satisfy their energy demands through the grid. With this in mind, subsidized financial programmes for small-scale domestic RES projects should be promoted by governments worldwide to encourage individuals to use RES to cover their power requirements.

HARI is one of the world's most well-known projects that use different renewable technologies to supply electrical power to domestic and office loads (Little et al., 2007). It is installed at West Beacon Farm, Leicestershire, UK. The project comprises wind turbines, photovoltaic panels and micro-hydro turbines because is located near a river. Concerning buffering, hydrogen technologies via electrolysis and a battery bank are also used. All these components are connected in a high voltage DC bus which cooperates with an AC bus from the national grid.

Simple and less costly renewable systems exist that can operate in combination with the grid and can cover the largest amount of energy consumed during a whole year. Such systems are based exclusively on solar energy, can be integrated into a building's design without destroying its aesthetic concept, and are characterized as small-scale because each operates autonomously to cover the building's demands. A simulated scientific research project in Andalusia, Spain, revealed that the energy from photovoltaic panels mounted on rooftops can satisfy 78.89% of all energy needs (Ordonez et al., 2010). The energy consumption for uses related to residential housing in Andalusia was 12,320 GW/year. If photovoltaic arrays were installed on all the available building rooftops the energy gain was calculated at 9,730 GW/year. This means that the national grid would have a backup role and if energy efficiency was increased in combination with a reduction in energy consumption, this Spanish community would be a totally green and autonomous area with its own electric grid (Ordonez et al., 2010).

2.3.2 THE-EVOLUTION OF RES BASED SYSTEMS: OFF-GRID SYSTEMS

The main future aim of RES-based systems is to reduce dependence of the population on fossil fuels and to meet its energy production demands. An attractive option towards optimization of global electrification in terms of environmentally friendly solutions is the development of off-grid supplied electricity systems. These hybrid systems are characterized by zero pollutant emissions and the lack of excessive operation and maintenance costs. Such systems are currently established in isolated remote areas for rural electrification where connection to the national grid is difficult and expensive (Bekele & Tadesse, 2012). Several studies exist on single and hybrid projects that prove the feasibility of such a scenario. Figure 2.4 presents a typical stand-alone system which is not supported by a national AC grid.

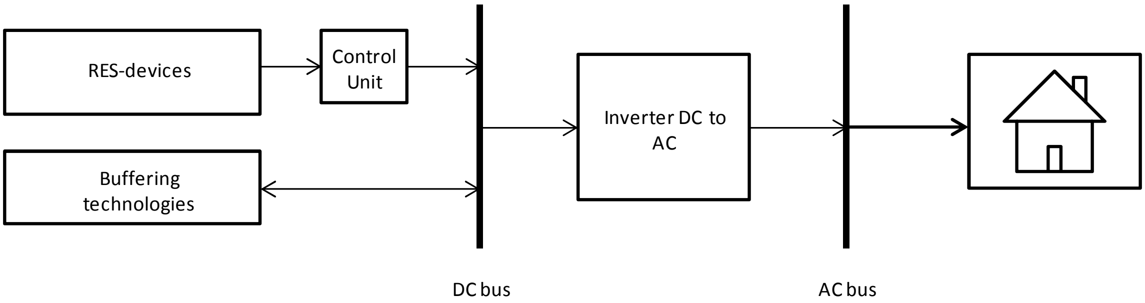


Figure 2.4 A typical off-grid RES-based hybrid system.

Several scientific approaches exist for already established or simulated systems based on RES technologies to cover the electricity demand problems of isolated islands (Kaldellis et al. 2009, Katsaprakakis et al. 2012) and remote communities far from a national grid, especially in poor countries (Youma et al., 2000). Such systems which include wind and solar parks or hydropower technologies and meet huge electrical loads, are included in large-scale projects.

Many small tourist lodgings in Australia are remote and have to rely on stand-alone power supply systems, comprising diesel generators (Dalton et al., 2009). In these cases, a feasibility analysis of renewable energy supply was performed and presented optimistic results for small- to medium-scale tourist operations (less than 100 beds) to lose dependence on fossil fuels. Using simulations, the main sources used for energy production were the wind and solar potential in combination with back-up energy from a battery bank. The data and subsequent modeling demonstrated that RES is both technically feasible and economically viable compared to diesel energy supply for small- to medium-scale investments. In the same study, hydrogen technologies were tested to replace batteries for energy storage, but were proved not to be economically viable in the case studies concerned, due to the present high cost of components, especially compared to existing diesel generators (Dalton et al., 2009).

Another study which reveals the importance and feasibility of RES based autonomous systems was undertaken in the extreme climatic conditions of Antarctica (Tin et al., 2010). This study presented a range of small-scale energy efficiency and renewable energy deployments within Antarctic research stations and field camps. Transportation and storage of large amounts of fossil fuel under this harsh environment involves major economic costs and environmental risks. Therefore, with the technological evolution of RES based equipment the desire to run entire stations or field camps on totally renewable energy is increasingly common and feasible. The electrical requirements of Antarctic research stations are small compared to urban installations on other continents. If renewable energy efficiency can be employed at a feasible level in the coldest, darkest and most remote area of the world, then the deployment of RES based autonomous systems should be more widespread and encouraged on other continents (Tin et al., 2010).

In other cases, the governments of poor countries take advantage of renewable sources to develop small-scale projects to supply electricity to remote rural communities and improve livelihoods and reduce poverty. Solar panels can meet these demands and specific research on the PERMER project in Argentina reveals that small stand-alone systems based on PV electricity provide better quality light, reduce indoor air pollution levels, and extend hours for cultural and productive activities. This RES based equipment was to be installed in homes, schools and public buildings sponsored by a range of public and private sources (Alazraki & Haselip, 2007).

Finally, from the above review on several stand-alone RES hybrid systems it is clear that the efficiency of energy production processes as well as the optimal adjustment between the load coverage and the consumption of specific parts of a stand-alone power system is crucial to eliminate energy waste. Additionally, the growing use of RES provides an optimistic prospect for the future, especially if their one serious drawback, that of energy storage, can be solved (Akella et al. 2007, Sreeraj et al. 2010).

A major obstacle - The main drawback characterizing all RES based autonomous systems is that the environmental energy potential is quite unpredictable since it fluctuates with time and is strongly dependent on local meteorological conditions (Abdullah et al., 2010). For this reason, the thorough study of local meteorological data is needed to design off-grid systems, but the major difficulty is the choice of a suitable energy storage unit. An optimum energy storage system must maintain its zero emission character, low lifecycle costs, and the longevity of the entire autonomous system.

Temporary energy buffering in storage systems is crucial for an uninterruptable energy supply, especially for standalone RES based systems. These systems are categorized according to their supplied energy in combination with their initial costs. Besides the well-known electrochemical batteries, numerous buffering technologies are used in mobile or medium-scale applications such as hydrogen technologies, super capacitors and compressed air pumps (Wang et al., 2013). It has been proven that the most conventional and commercialized way to overcome the buffering problem is through the use of batteries, which take advantage of new hi-tech materials that extend their lifetime, thus minimizing their size and increasing their power outputs (Prodromidis & Coutelieris 2011).

To summarize Chapter 2, since environmental pollution has increased dramatically and carbon fuel reserves are decreasing, Renewable Energy Sources (RES) appear to be a significant alternative providing a sustainable and environmentally friendly solution to the global energy problem.

Combining RES-technologies can lead to the building of a hybrid system which produces electrical energy to support the national AC grid or directly supply AC devices for domestic use in small-scale projects. The most promising use for such applications is the design of autonomous RES based hybrid systems with a totally eco-friendly zero emission character, in remote locations where the national grid cannot be extended due to cost limitations or the geographical terrain is harsh.

Finally, the main drawback of stand-alone systems, on storage energy part of such a hybrid system, is introduced here. This drawback will be analyzed in a following chapter together with its solution of alternative buffering systems that support RES-technologies in off-grid projects.

The next chapter will present the results from the simulation of several on- and off-grid RES projects and how they can be optimized to become feasible solutions in everyday real-life operational scenarios.

Box 2 Summary of RES technologies.

3 SIMULATION AND OPTIMIZATION ANALYSIS OF SEVERAL RES BASED PROJECTS

This chapter begins with the presentation of the energetic and economic simulation and optimization of an RES based stand-alone system that is already installed in Leicestershire, UK. Based on local meteorological data, an optimization strategy has been developed to identify the most economical and efficient scenarios for the generation of electricity to cover the desirable load on an annual basis. Furthermore, the environmentally friendly character of the system was highly concerned with emissions reduction, and therefore the energy producing potential of an off-grid system was also investigated. The chapter then concentrates on the feasibility of RES based systems to supply electricity to four different Greek Islands. Three specific typical loads were selected to be covered, and the grid connection was considered optional. The simulation and optimization procedures in both parts of the present chapter were applied using HOMER software in order to investigate the world's most well-established stand-alone system.

3.1 SIMULATION AND OPTIMIZATION OF AN AUTONOMOUS RES BASED POWER PLANT

Background - The major problem that arises from the combined use of RES to cover a given energy load is the selection and adjustment of parameters related both to energy and economy, in order to obtain optimum energy coverage and economical performance of the system. Several attempts have made on the accurate selection of parameters for optimum energy and economical results and not only to promote the ecological character of certain systems (Elhadidy & Shaahid 2000, Wichert 1997) but also for them to run off-grid, such as that located at West Beacon Farm, Leicestershire, UK. The RES based power plant of West Beacon Farm was constructed within the framework of the HARI project in 2001 and forms the case study of the present work (Gammon et al., 2006). The design and construction of the UK plant were published by Little et al. (2007). At that time the whole plant had not been optimized, thus a connection with grid was essential to cover the electric load. The researchers observed that certain technologies, such as hydrogen, hydroelectric and photovoltaic panels, were of low efficiency and that the initial and operational costs were substantial (Little et al., 2007).

These two main drawbacks, as shown previously, can be overcome indicating that an autonomous system can be economically feasible (Elhadidy and Shaahid 2000, Wichert 1997) whereas the appropriate technologies should be selected in accordance with the local climatic conditions (Muselli et al., 1999). The present part of this thesis aims to present the combined use of RES in a power plant designed in an optimum way. Apart from optimizing the system, it is also essential to propose other combinations of RES using the simulations. Clearly the characteristics of the renewable resources influence the behavior and economics of renewable power systems (Tsikis & Coutelieris, 2009). For this reason all the different scenarios presented here include different renewable sources, i.e. solar energy, wind energy, hydropower and hydrogen (produced mainly by electrolysis) as well as combinations of these.

Simulation process - The installed unit at West Beacon Farm uses: (a) two Carter 25 kW Wind Turbines (WT), (b) a fixed array of photovoltaic panels (PV), consisting of 3 kW monocrystalline modules and 3 kW polycrystalline ones, (c) approx. 3 kW hydroturbines (Hydro), run by water flowing through a storage engine, (d) a 15 kW LPG Internal Combustion Engine (ICE), and (e) a 7 kW PEM Fuel Cell (FC) stack, that utilizes pure hydrogen stored in a high pressure storage tank (Figure 3.1). All these sources are supported by a single 20 kW Zebra battery and the system supplies electrical power to a residential house and a group of offices (Little et al., 2007).

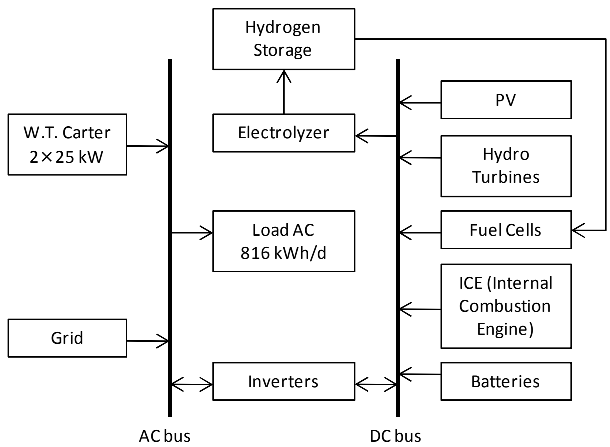


Figure 3.1 Schematic view of the RES based system at West Beacon Farm, Leicestershire, UK.

Further to the installed plant, several alternative systems of different topologies and devices are also examined. These topologies build up the different scenarios for the load coverage and are analytically presented in Table 3.1. It is worth noticing that all the scenarios must cover the desirable load and the peak electricity demand, while the unmet load should be minimized. All the scenarios in this project were set up on the software optimization tool HOMER (Hybrid Optimization Model for Electric Renewables) (http://www.nrel/gov/HOMER) that is capable of simulating systems of different RES by using hourly data for the load (Bernal-Agustin & Dufo-Lopez, 2009).

	Description						
Scenario Codes	Wind turbines (kW)	PV module (kW)	Hydro power (kW)	Internal Combustion Engine (kW)	Fuel Cell (kW)	No. of batteries (Zebra, 20 kW each)	Grid
1a	Carter 2×25	6	3	15	7	1	Yes
1b	Carter 2×25	13				246	No
2	PGE 2×25					13	No
3a	PGE 1×25			34			No
3b	PGE 1×25			34		1	No

Table 3.1. Description of different simulation scenarios.

For all the simulations performed, the nominal interest rate and the annual inflation rate were considered as constant and equal to 7.5% and 3%, respectively. The elements of the photovoltaic arrays used in the simulations were determined by the study of m-Si technology, their orientation and their instrumentation (Duffie & Beckman 1980). For the wind turbines (Carter Wind Systems) and Zebra batteries, specifications from the manufacturer's manuals were used. For the internal combustion engine, the emissions were added separately (Murillo et al., 2005), while for the economic study the costs used were the same as those of the established system (Gammon et al., 2006). In addition, meteorological data were collected from several local meteorological stations.

Results and General discussion - The established unit was simulated in HOMER, and the results are depicted in Figure 3.2. The figure shows that the highest portion of electrical energy comes from the grid and the wind turbines. On the other hand, photovoltaic panels and hydrogen seem to have a small influence on the coverage of the desirable load. This mainly occurs because the system has not been optimized, and the original design intended to cover a constant load at the peak value of consumption without taking a normal daily variation into account (Little et al., 2007). The real desirable load was assumed to be much smaller, therefore a second simulation was performed for the same unit with a different, more feasible load, thus reducing the load by more than 50 %.

Limiting the simulated desirable load to a more realistic level was proposed after examining the true electricity consumptions of the different apparatuses used in the present case study. It is known that this RES system has to supply electricity to an office block and a domestic residence that are both equipped with common devices, concerning their consumption, to cover standard human living requirements (Little et al., 2007). Therefore, by following a typical everyday life timetable for such buildings the more realistic electrical needs for stable operation of the system for one whole year can be easily calculated. Figure 3.2 shows that the contribution of the grid supply to the total consumption becomes smaller when the load is decreased but it remains significant enough for an optimization procedure to be necessary.

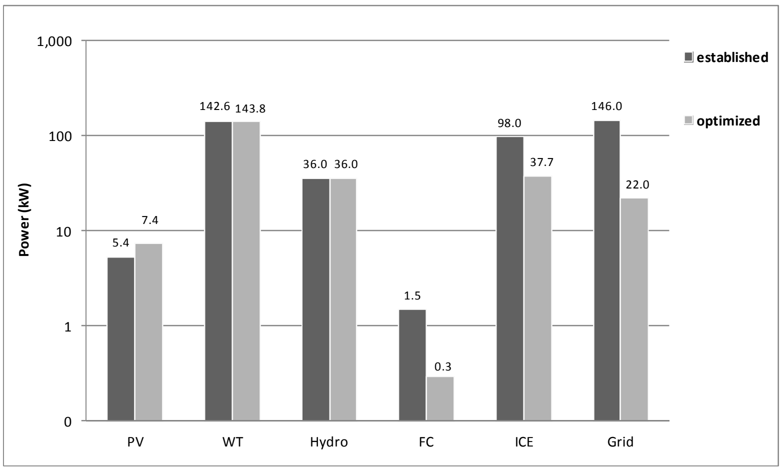


Figure 3.2 Electricity production per RES device of the West Beacon Farm system to cover the peak electricity demands (established) and a more realistic load (optimized).

The results of these simulations show that the final choice of load measurements must be based on scenario 2 (Figure 3.3). Technologically newer wind turbines take greater advantage of the wind's power so the production of electricity is extremely high and excess electricity can be used to cover the thermal load or can be sold to the grid if there is a connection.

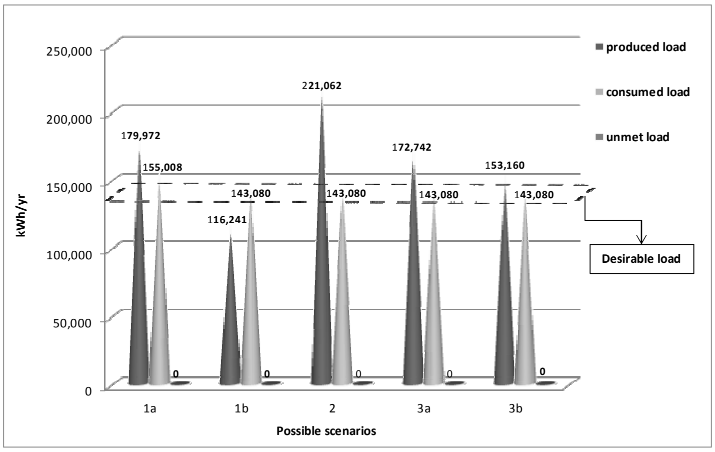


Figure 3.3 Comparison of the different scenarios in terms of electricity production.

The comparison between the different scenarios for the lowest pollutant emissions is presented in Figure 3.4, where scenario 2 appears to be the most preferable because it is totally "green" with zero emissions. Moreover, for scenario 3a and scenario 3b, pollutant emissions are increased because of the use of the internal combustion engine and the grid connection (if any).

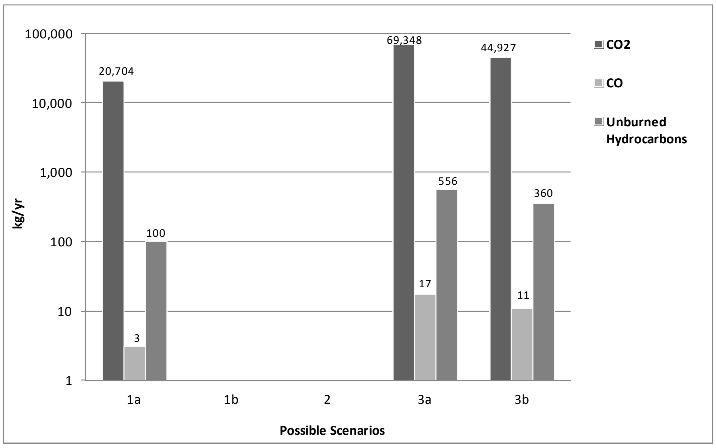


Figure 3.4 Comparison of the emissions per scenario.

Concerning the economic criteria, the preferable scenario will theoretically be that with the lowest initial, operational and overall costs over a 25 year life-span. All the scenarios were compared from an economic point of view and the results are presented in Figure 3.5. The figure shows that the scenarios with internal combustion engines have low initial costs but over the years the total amount of money that must be spent is very high because of fuel prices.

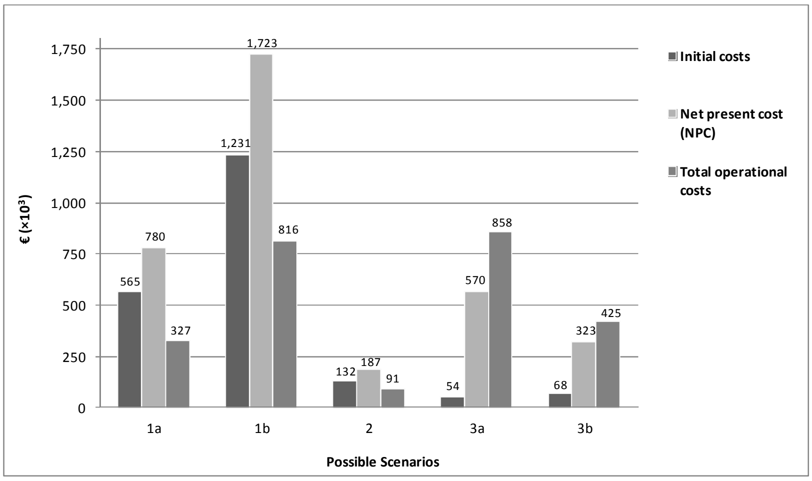


Figure 3.5 Economic comparison of each scenario.

On the other hand, the units that exclusively use RES (scenario 1b & scenario 2) have high initial costs but low operational costs. Furthermore, even though hydrogen is a promising technology, it appears to be too expensive to replace other, more mature, RES. Conclusively, scenario 2 remains the best option because it satisfies the economical criteria.

General conclusion - By using HOMER software, different scenarios for the coverage of the desirable electric load were studied for the established system of West Beacon Farm, UK. The optimization process of the system by using a more realistic load and different combinations of RES technologies, and according to the local meteorological data, was essential to produce the improved results that will be presented hereafter. Therefore, in this section 3.1, several different feasible ways to cover an electric load with a combined usage of different “green” technologies were investigated. The grid connection was found to be inessential and at the same time the total costs can be significantly decreased. Specifically, scenario 2 presented

22.8% better load coverage (without a grid connection), 100% lower pollutant emissions level (zero emissions) and 76% lower total cost (76.6% decrease for initial and 72.2% for operational costs).

3.2 A Comparative Feasibility Study of Stand-Alone and Grid Connected RES Based Systems on Several Greek Islands

Background - Even though special effort has been given to optimize stand-alone hybrid systems in terms of both energy and economy feasibility (Celik 2002, Akella et al. 2007), the major obstacle of selecting the optimal components for energy coverage with the most efficient economical performance, still remains. Furthermore, another major problem is the high overall cost needed to continuously supply the electrical load via the grid connection, especially for isolated areas such as some of the Greek islands. Another difficult situation that isolated Greek Islands face is the outage of the electric power when unfavorable climatic conditions prevail, especially in winter with very strong wind potential. Under these conditions, much damage can occur to the national grid and some islands can remain without electricity for several days of the year. Therefore, it is crucial to optimize RES based units located in isolated areas so they operate continuously.

It is possible to overcome these drawbacks by designing an autonomous power plant, and selecting technologies that suit the prevailing climatic conditions (Abdullah et al., 2010). Several studies have shown that the final selection of the renewable resources in a project influence its financial and energy balance.(Singal et al. 2007, Elhadidy & Shaahid 2000, Muselli et al. 1999, Tsikis & Coutelieris 2009).

Towards such a solution, three different typical loads (one for a typical house, one for a typical country house and one for a typical small enterprise) were chosen for the feasibility study. It was supposed that the RES systems were all established on four different Greek Islands, distinguished by climatic conditions (sun-rays and wind potential). Using these typical loads, different scenarios were created and optimized in terms of energy efficiency and economic feasibility based on the theoretical background presented in chapter 2.1 and chapter 2.2

respectively. All these scenarios were assumed to utilize solar and wind energy, either separately or simultaneously.

The existence of a stack of batteries or an ICE is crucial for constant operation of stand-alone systems. These are not used only as backup energy systems but they also replace the power characteristics of the grid. The apparatus operate on a local grid under firmly specified operational characteristics (220 V, 50 Hz). Therefore, a control unit is necessary to receive the local grid's specifications for the accurate combination of the several RES components. In the present study, Zebra batteries were used exclusively because the cost of fuel used in ICE systems, increases greatly the number of abbreviation years while additionally, one of the main objectives is the production of zero emissions systems.

Simulation process - Four different Greek islands were selected for the simulations, namely Crete (Rethimnon prefecture), Rhodes, Skiros and Naxos, as shown in Figure 3.6. Meteorological data for these sites was obtained from local meteorological stations available online (http://www.cres.gr).

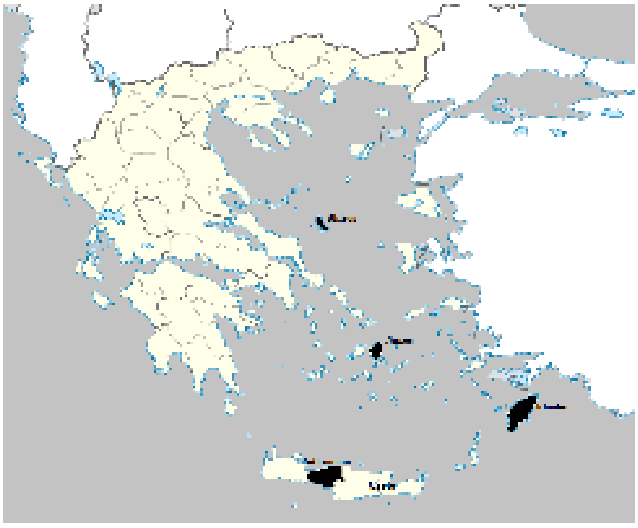


Figure 3.6 The four Greek Islands used for the simulations.

The specific Greek Islands were selected following extensive study of their meteorological data, monthly average solar radiation, monthly average wind speed and their whole environmental potential in general. Therefore, the main selection criterion was the number of solar-biased months, wind-biased months and the combination of both solar- and wind-biased months. The study of meteorological data revealed the core environmental energy source of each island and aided the selection of the best value for money RES system in each case. Figure 3.7a & Figure 3.7b present the monthly average solar and wind potentials per island, respectively.

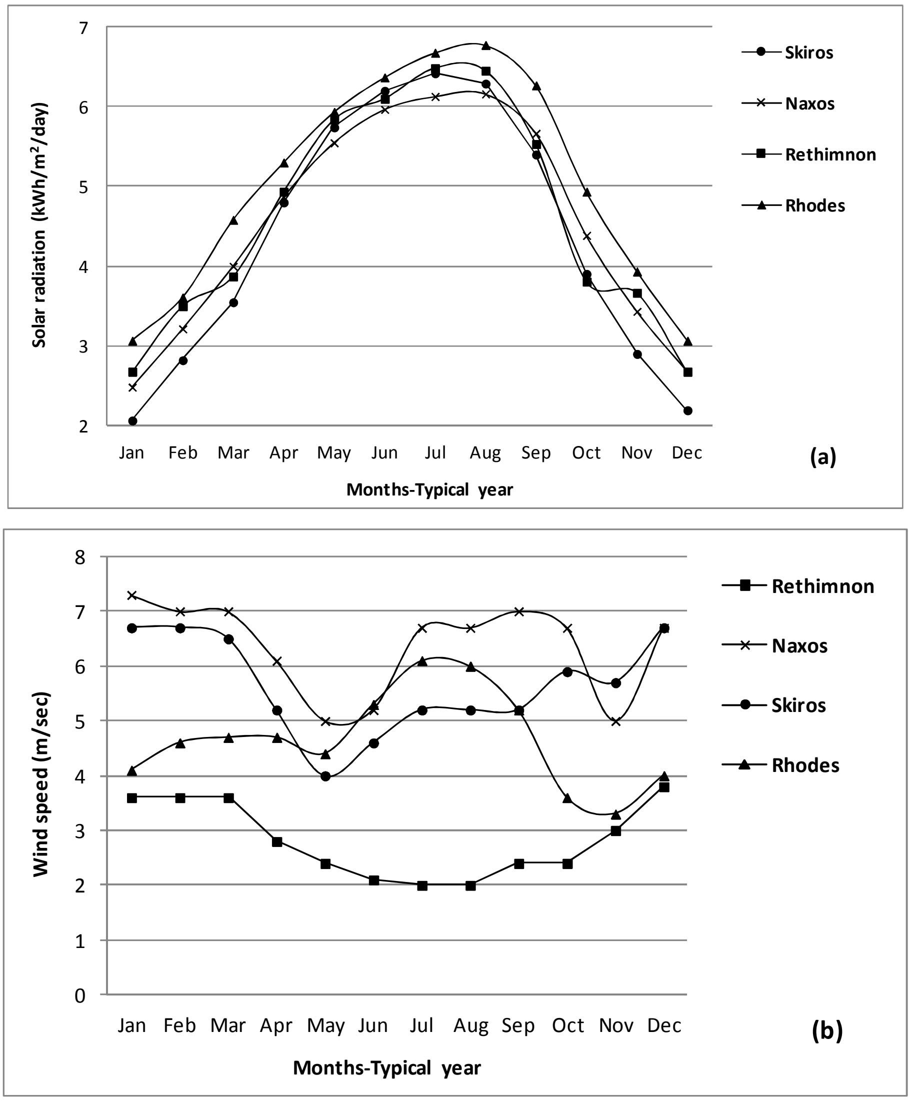


Figure 3.7 Solar (a) and wind (b) potentials for each island.

The next step was to construct three different systems (a single photovoltaic, a single wind turbine, and a hybrid photovoltaic-wind system) as shown in Figure 3.8a, Figure 3.8b and Figure

3.8c. These components were used to cover three different desirable loads, one corresponding to a typical house, one to a typical country house, and one to a small company established in a small building.

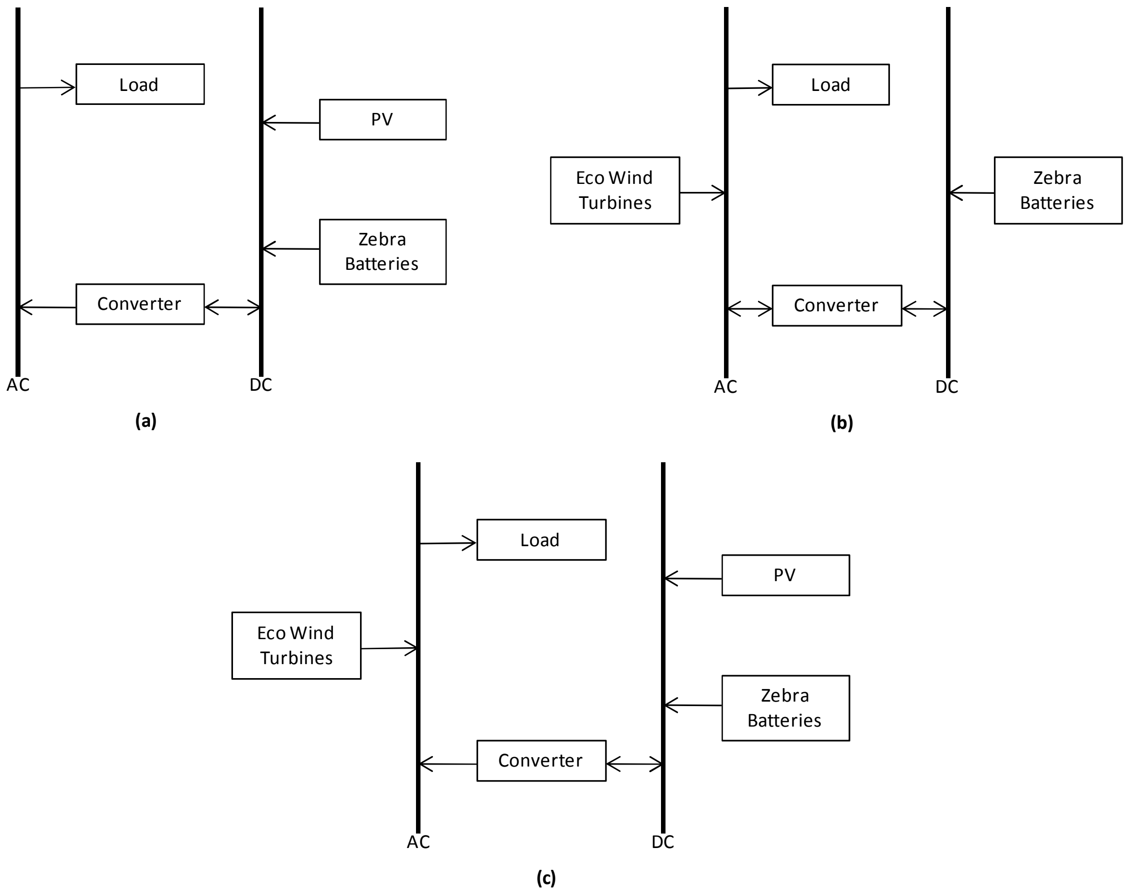


Figure 3.8 The components for a single photovoltaic (a), a single wind turbine (b), and a hybrid photovoltaic-wind (c) system.

The HOMER software allows the selection of the desirable load on an hourly basis for each month of one whole year. In this study, the typical year was separated into three periods and for each simulated period the days were also separated into two categories: weekend and weekday. The sums of these loads for the weekdays and weekends of each period and for each case, are presented in Figures 3.9a-c.

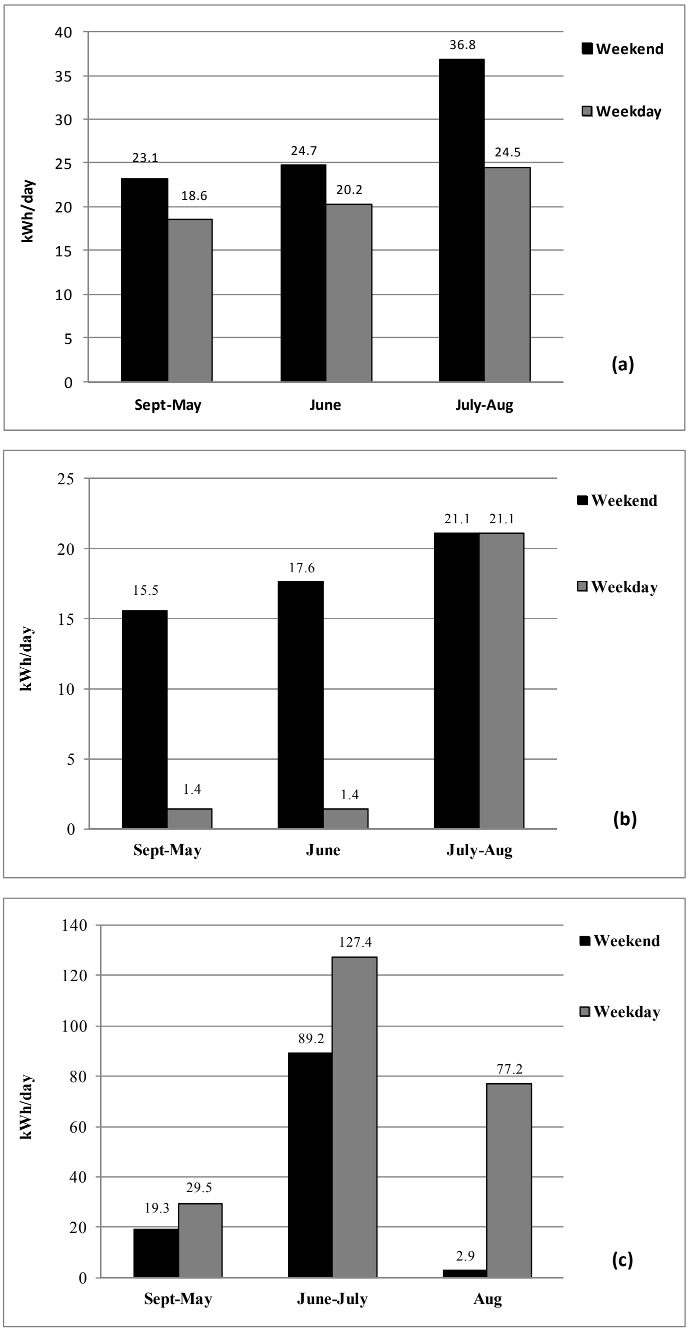


Figure 3.9 Average load requirements per day for a typical house (a), a typical country house (b), and a typical small enterprise (c).

The three different loads are analytically presented in Table 3.2. Their selection was made based on the energy consumed on an hourly basis during a typical year. Choosing the correct loads can be problematic because several different parameters must be taken into account, such as the air-conditioning during summer and the devices that operate normally or on standby mode during the whole year. In this respect, the optimization of these scenarios, in any location, would clarify if the use of a stand-alone system is economically feasible for a small individual consumer.

Time (h)	Consumption for September-May (kWh)		Consumption for June (kWh)		Consumption for July-August (kWh)	
	Weekday	**Weekend**	**Weekday**	**Weekend**	**Weekday**	**Weekend**
00:00-01:00	1.760	1.500	1.860	1.600	2.300	2.300
01:00-02:00	0.300	0.300	0.400	0.400	1.000	2.100
02:00-03:00	0.280	0.200	0.400	0.300	1.000	2.000
03:00-04:00	0.054	0.054	0.154	0.154	1.000	1.000
04:00-05:00	0.054	0.054	0.154	0.154	1.000	1.000
05:00-06:00	0.054	0.054	0.154	0.154	1.000	1.000
06:00-07:00	1.100	0.054	1.200	0.154	1.100	1.000
07:00-08:00	0.700	0.054	0.700	0.154	0.700	1.000
08:00-09:00	0.040	0.054	0.040	0.154	0.040	1.000
09:00-10:00	0.040	0.500	0.040	0.600	0.040	0.500
10:00-11:00	0.040	2.400	0.040	2.400	0.040	2.400
11:00-12:00	0.040	1.100	0.040	1.100	0.040	1.100
12:00-13:00	0.040	0.400	0.040	0.400	0.040	0.400
13:00-14:00	0.300	3.000	0.400	3.100	0.400	3.100
14:00-15:00	0.300	1.500	0.400	1.600	0.400	1.600
15:00-16:00	2.000	0.300	2.100	0.400	2.100	1.200
16:00-17:00	2.000	3.500	2.100	3.600	2.100	4.600
17:00-18:00	1.500	0.500	1.600	0.600	1.600	1.800
18:00-19:00	1.000	0.400	1.100	0.500	1.100	0.500
19:00-20:00	1.000	1.000	1.100	1.000	1.100	1.000
20:00-21:00	1.000	1.000	1.100	1.000	1.100	1.000
21:00-22:00	2.500	2.500	2.600	2.500	2.600	2.500
22:00-23:00	1.000	2.000	1.000	2.000	1.100	2.000
23:00-00:00	1.500	0.700	1.500	0.700	1.600	0.700
SUM	**18.600**	**23.124**	**20.222**	**24.724**	**24.500**	**36.800**

(a)

Time (h)	Consumption for September-May (kWh)		Consumption for June (kWh)		Consumption for July-August (kWh)	
	Weekday	**Weekend**	**Weekday**	**Weekend**	**Weekday**	**Weekend**
00:00-01:00	0.060	0.500	0.060	0.600	0.600	0.600
01:00-02:00	0.060	0.400	0.060	0.500	0.500	0.500
02:00-03:00	0.060	0.060	0.060	0.160	0.160	0.160
03:00-04:00	0.060	0.060	0.060	0.160	0.160	0.160
04:00-05:00	0.060	0.060	0.060	0.160	0.160	0.160
05:00-06:00	0.060	0.060	0.060	0.160	0.160	0.160
06:00-07:00	0.060	0.060	0.060	0.160	0.160	0.160
07:00-08:00	0.060	0.060	0.060	0.160	0.160	0.160
08:00-09:00	0.060	0.060	0.060	0.160	0.160	0.160
09:00-10:00	0.060	0.500	0.060	0.500	0.500	0.500

10:00-11:00	0.060	0.800	0.060	0.800	0.800	0.800
11:00-12:00	0.060	0.400	0.060	0.400	0.400	0.400
12:00-13:00	0.060	0.400	0.060	0.500	0.500	0.500
13:00-14:00	0.060	3.000	0.060	3.100	3.100	3.100
14:00-15:00	0.060	1.500	0.060	1.600	1.600	1.600
15:00-16:00	0.060	0.300	0.060	0.400	2.000	2.000
16:00-17:00	0.060	0.300	0.060	0.400	1.500	1.500
17:00-18:00	0.060	0.600	0.060	0.700	1.500	1.500
18:00-19:00	0.060	0.400	0.060	0.500	0.500	0.500
19:00-20:00	0.060	1.000	0.060	1.100	1.100	1.100
20:00-21:00	0.060	2.000	0.060	2.100	2.100	2.100
21:00-22:00	0.060	2.000	0.060	2.100	2.100	2.100
22:00-23:00	0.060	0.500	0.060	0.600	0.600	0.600
23:00-00:00	0.060	0.500	0.060	0.600	0.600	0.600
SUM	**1.440**	**15.520**	**1.440**	**17.620**	**21.120**	**21.120**

(b)

Time (h)	**Consumption for September-May (kWh)**		**Consumption for June-July (kWh)**		**Consumption for August (kWh)**	
	Weekday	**Weekend**	**Weekday**	**Weekend**	**Weekday**	**Weekend**
00:00-01:00	0.120	0.120	0.120	0.120	0.120	0.120
01:00-02:00	0.120	0.120	0.120	0.120	0.120	0.120
02:00-03:00	0.120	0.120	0.120	0.120	0.120	0.120
03:00-04:00	0.120	0.120	0.120	0.120	0.120	0.120
04:00-05:00	0.120	0.120	0.120	0.120	0.120	0.120
05:00-06:00	0.120	0.120	0.120	0.120	0.120	0.120
06:00-07:00	0.120	0.120	0.120	0.120	0.120	0.120
07:00-08:00	0.120	0.120	0.120	0.120	0.120	0.120
08:00-09:00	2.160	0.120	2.160	0.120	2.160	0.120
09:00-10:00	2.160	2.160	2.160	2.160	2.160	0.120
10:00-11:00	2.160	2.160	14.160	14.160	14.160	0.120
11:00-12:00	2.160	2.160	14.160	14.160	14.160	0.120
12:00-13:00	2.160	2.160	14.160	14.160	14.160	0.120
13:00-14:00	1.200	2.160	14.160	14.160	14.160	0.120
14:00-15:00	1.200	1.200	14.160	14.160	14.160	0.120
15:00-16:00	2.160	1.200	14.160	14.160	0.120	0.120
16:00-17:00	2.160	2.160	14.160	0.120	0.120	0.120
17:00-18:00	2.160	2.160	14.160	0.120	0.120	0.120
18:00-19:00	2.160	0.120	2.160	0.120	0.120	0.120
19:00-20:00	2.160	0.120	2.160	0.120	0.120	0.120
20:00-21:00	2.160	0.120	2.160	0.120	0.120	0.120
21:00-22:00	2.160	0.120	2.160	0.120	0.120	0.120
22:00-23:00	0.120	0.120	0.120	0.120	0.120	0.120
23:00-00:00	0.120	0.120	0.120	0.120	0.120	0.120
SUM	**29.520**	**19.320**	**127.440**	**89.160**	**77.160**	**2.880**

(c)

Table 3.2 Real-life loads for a typical house (a), a typical country house (b), and a small company (c) during one day in each period.

The second step was re-design of the same systems used in step 1, this time including two external limitations: the surface area available for the installation of the systems was fixed to 5,000 m^2 in each case, and the capital costs of the components should not exceed 100,000 €. The above restrictions could be considered feasible in Greece for a small to medium-scale consumer aiming for independence from the national grid in order to save money by using RESs. For this reason, in the simulations the desirable load had to be covered and any excess electricity could be sold to the grid, to reduce the amount of the abbreviation years of the systems. It is important to note that the grid-connection for each system was always one-way: the system can offer electricity to the grid but can never receive electricity from it.

Finally, the island with the highest energy environmental potential was selected for the design of the optimal system to cover the desirable load of a typical house using three different combinations of RES components: a single photovoltaic system, a single wind turbine system, and a hybrid photovoltaic-wind system. All three used Zebra batteries to store excess electricity. This scenario with the same components was simulated using meteorological data of the several selected Greek islands to identify any relation between the energy received from the environment and the total energy is produced by the components of the RES based systems.

As the optimal ratio of energy load can be obtained from several combinations of photovoltaic panels and wind turbines, it is necessary for a researcher to optimize each system by selecting the most suitable components for a given specific area. For this reason, all the scenarios presented here used multi-crystalline panels (Duffie & Beckman, 1980) with performances of approx. 15% in real-life conditions. Furthermore, wind velocity varies greatly during the year, therefore it was considered appropriate to select specific wind turbines that start their operation at relatively low wind velocities (≈ 2.5 m/sec), and are affordable to an individual consumer. Eco Wind Turbines (http://www.ecowindturbine.com) of 5 and 10 kW fulfilled the exact requirements of this study. Finally, the Zebra batteries used for storing the excess electrical load have a longer operational life compared to competitive technologies. For the wind turbines and Zebra batteries, all the parameters necessary for the simulations were taken from the manufacturers' manuals (Dustmann, 2004).

The financial study of these projects was be finalized by the depreciation of the system's capital costs over time which was estimated by either Equation 2.12 or 2.13 according to each examined case. It should be mentioned that for the scope of the present work, the second term of Equation 2.9 is equal to zero because the salvage value, S, is zero at the end of each component's lifetime. Furthermore, $f_{rep.}$ in the first factor of Equation 2.9, arises because a component's lifetime can differ from the project's lifetime. This factor is equal to the unit since the end of the project coincides with the replacement of the component at which the above expression is referred to. Finally, the actual interest rate is considered constant and equal to 5%. The lifetime project is not a constant parameter because the desirable aim of this research is to be calculated the operating period of the project under which the simulated project can be profitable for a future investor. Moreover, the factor $N_{comp.}$ in Equations 2.9 & 2.11 is the lifetime of each component and not the lifetime for which each RES-project is designed for. This factor is calculated separately for each component and then summed to determine the total annual replacement costs.

Results and General discussion - All the possible scenarios were designed using HOMER software. The energy results of this project were based on HOMER but the economic study was divided into three different parts to calculate the amount of the abbreviation years for each system. The emissions costs, the money gained from trading of the excess electricity back to grid take part in the calculations, the project's lifetime is not considered as constant and the annual replacement costs are estimated separately for each component. It is obvious that the produced electric load is the most crucial parameter for the feasibility of a RES based system so the meteorological data play the most important role in the above calculations because the energy production is owed to climatic conditions. As concern the grid its connection only accounts for the sale of the excess electricity.

The scenarios were designed as presented in Table 3.3. It should be noted that the 7775 kW, 2982 kW and 16097 kW values refer to the annual desirable load of the typical house, the typical country house and the typical small enterprise, respectively. It can be seen from Table 3.3 that the hybrid systems can operate with different combinations of components (**pv_bat**: photovoltaic + batteries, **wind_bat**: wind turbines + batteries, **pv_wind_bat**: the combination of the three components) but the most economically feasible solutions have been selected to show in Table 3.3, as above described.

		CRETE (RETHIMNON)			**RHODES**			**SKIROS**			**NAXOS**		
	Desired load (kW)	PV (kW)	Wind (kW)	Zebra 20 kW (1)	PV (kW)	Wind (kW)	Zebra 20 kW (1)	PV (kW)	Wind (kW)	Zebra 20 kW (1)	PV (kW)	Wind (kW)	Zebra 20 kW (1)
pv_bat	7775	7	-	1	6	-	1	7	-	1	7	-	1
	2982	5	-	1	5	-	1	5	-	1	5	-	1
	16097	28	-	2	25	-	4	25	-	3	25	-	4
wind_bat	7775	-	4×10	4	-	2×10	1	-	1×5	1	-	1×5	1
	2982	-	2×5	5	-	1×5	1	-	1×5	1	-	1×5	1
	16097	-	14×10	18	-	2×10	3	-	3×10	1	-	2×10	4
pv_ wind _bat	7775	6	1×5	1	3	1×5	1	1	1×5	1	1	1×5	1
	2982	3	1×5	2	1	1×5	1	1	1×5	1	1	1×5	1
	16097	25	1×5	4	19	1×5	2	19	2×5	1	21	1×5	2

Table 3.3 Optimum scenarios for each location.

The same meteorological conditions and the same values for the economical parameters also apply for the second step of this study. The scenarios with the constraint of investment costs (100,000 €) are presented in Table 3.4. The systems which are not accomplished with the economical and territorial restrictions cannot be designed and therefore they have been omitted from the time abbreviation analysis. The three different optimum systems for the coverage of the load of a typical house, which is established on Naxos Island, are presented in Table 3.5. The latter has been selected because Naxos, as Figure 3.7a and Figure 3.7b show, is the island with the largest environmental potential and the typical house has a load characteristic of an individual consumer exactly the same in each selected Greek island.

		CRETE (RETHIMNON)			RHODES			SKIROS			NAXOS		
	Desired load (kW)	PV (kW)	Wind (kW)	Zebra 20 kW (1)	PV (kW)	Wind (kW)	Zebra 20 kW (1)	PV (kW)	Wind (kW)	Zebra 20 kW (1)	PV (kW)	Wind (kW)	Zebra 20 kW (1)
pv_bat	7775	35	-	1	35	-	1	35	-	1	35	-	1
	2982	35	-	1	35	-	1	35	-	1	35	-	1
	16097	35	-	1	35	-	1	35	-	1	35	-	1
wind_bat	7775	-	2×10	1	-	2×10	1	-	2×10	1	-	2×10	1
	2982	-	2×10	1	-	2×10	1	-	2×10	1	-	2×10	1
	16097	-	-	-	-	-	-	-	-	-	-	-	-
pv_ wind _bat	7775	25	1×5	1	25	1×5	1	25	1×5	1	25	1×5	1
	2982	25	1×5	1	25	1×5	1	25	1×5	1	25	1×5	1
	16097	-	-	-	25	1×5	1	25	1×5	1	25	1×5	1

Table 3.4 Scenarios per location under the investment limitation.

Typical House (7775 kWh/year)			
systems	PV (kW)	Wind (kW)	Zebra 20 kW (1)
pv_bat	6	-	1
wind_bat	-	1×5	1
pv_wind_bat	1	1×5	1

Table 3.5 Optimum systems for Naxos Island.

Table 3.6 shows that a stand-alone (off-grid) system is not financially profitable because the components are very expensive regarding their performance. Additionally, over sizing of the system is necessary for its constant operation. The grid connection changes dramatically the above results, as shown in Table 3.6, because the consumer takes advantage of the excess electrical power created by the over sizing and an important amount of money is earned from the trade of energy packages. The systems that exclusively use wind energy show the greatest failure to abbreviate the capital cost through time. This is because wind is a very unstable energy source and wind technologies have high capital costs.

	Location	**CRETE (RETHIMNON)**		**RHODES**		**SKIROS**		**NAXOS**	
	Desired load (kW)	years (no grid)	years (grid)	years (no grid)	years (grid)	years (no grid)	years (grid)	years (no grid)	years (grid)
pv_bat	7775	25.7	14.1	64.1	22.2	86.2	23.6	25.7	14.0
	2982	822.5	12.1	never	12.8	never	17.1	822.5	12.0
	16097	40.6	6.7	never	10.5	never	10.2	93.9	9.4
wind_bat	7775	never	never	never	8.8	203.8	14.8	203.8	9.4
	2982	never	never	never	20.5	never	10.1	never	7.3
	16097	never	never	never	16.4	never	4.7	never	6.1
pv_ wind _bat	7775	never	28.4	never	20.3	never	15.3	254.4	8.6
	2982	never	109.7	never	16.0	never	9.1	never	6.9
	16097	1294.8	12.1	never	9.0	146.0	6.0	75.7	6.4

Table 3.6 Abbreviation of the systems in years.

It is clear from the above results that for an established system to sell excess electricity, a connection to the grid is essential. Overall, the systems in Naxos present the shortest abbreviation periods (for a typical house the average amount of years for its time abbreviation is 8.6 years, for a typical country house 6.9 years, and for a small company 6.4 years). This is observed because Naxos has the greatest environmental potential and as much as the desirable electrical load increased, the excess electricity produced is greater due to component over-sizing.

In the final step, the analysis on the time abbreviation of the systems designed under the economical and territorial limitations will be finalized and presented below. The results in Table 3.7 show that the stand-alone systems cannot be abbreviated during a logical period of time, up to 10-15 years, because the over-sizing is much larger than the requirements of the systems. On the other hand, when the same systems are connected to the grid, the average abbreviation time is limited to five years or less. In this respect, an individual consumer should act virtually as a small businessman whether or not over-sizing is inevitable. The single wind systems again show the same unpredictable behavior as mentioned above.

		CRETE (RETHIMNON)		**RHODES**		**SKIROS**		**NAXOS**	
	Desired load (kW)	years (no grid)	years (grid)	years (no grid)	years (grid)	years (no grid)	years (grid)	years (no grid)	years (grid)
pv_bat	7775	745.9	4.7	745.9	4.1	745.9	4.7	745.9	4.4
	2982	never	4.4	never	3.9	never	4.5	never	4.4
	16097	37.5	5.1	37.5	4.4	37.5	4.9	37.5	5.1
wind_bat	7775	-	-	never	8.8	never	4.9	never	3.6
	2982	-	-	never	7.9	never	4.6	never	4.4
	16097	-	-	-	-	-	-	-	-
pv_wind_bat	7775	never	6.8	never	5.0	never	5.2	never	4.4
	2982	never	6.3	never	5.2	never	4.9	never	4.4
	16097	-	-	56.4	5.6	56.4	5.5	56.4	5.2

Table 3.7 Abbreviation of the systems in years under the investment limitation.

The above analysis revealed the relationship between the produced energy and the environmental potential for the three different scenarios supposed to satisfy the desirable load of a typical house. This relationship is depicted in Figure 3.10. In general, the electricity produced increases linearly with the environmental potential, presenting relatively high slopes, except of the case of the pv_bat system. In this case, an almost constant behavior is observed with a relatively low inclination of 0.36. This occurs because solar energy is generally stable without significant fluctuations due to location or surface area, especially in a Mediterranean country such as Greece. On the other hand, systems that take advantage of the wind depend on their location, underlining that a thorough environmental study on meteorological data is very important.

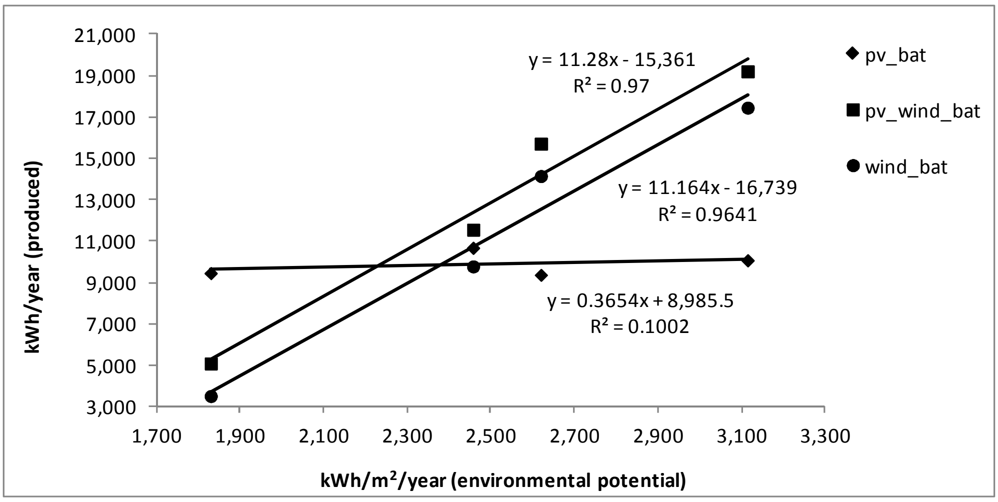


Figure 3.10 The produced electricity as a function of environmental potential.

General conclusion - Three different scenarios in four different Greek islands were studied. Each was based on RES technologies aiming to cover three different typical desirable loads. The simulations took place using a modified calculation system based on HOMER software. The years required for the time abbreviation of a system is a crucial parameter for the investor. The grid connection is found to be necessary not for energy backup but only to trade excess electricity from the RES components. A system located in an area with large environmental potential, namely Naxos Island, has a quite small abbreviation period (less than 10 years). Moreover, it is observed that a hybrid photovoltaic-wind system is more profitable than a single photovoltaic or a single wind system which need more energy packages than a typical house. The best results for the number of abbreviation years are achieved if small over-sizing is performed in order to feed the system regardless of the local environmental potential. Finally, the relationship between the produced energy and the environmental potential reveals the importance of the study of local meteorological data before the investment is made.

To summarize Chapter 3, two different studies were carried out focusing on the simulation of different RES based hybrid systems. In the study an already established system in Leicestershire, UK, was simulated and optimized using the HOMER platform. It was found that following **an accurate optimization technique** this system can be transformed into a stand-alone almost totally “green” system.

Secondly, three different small-scale scenarios on four Greek islands were examined to prove the necessity of energy and financial optimization process throughout the installation of a RES based application. **The simulations in this study were finalized using a modified calculation system based on HOMER software.** Using modified HOMER simulations for the selected hybrid scenarios was selected because the first study determined the weakness of the HOMER software simulation tool on the energy optimization analysis which is the most important element in the design of an RES based hybrid system, especially for remote applications. Therefore the selection of the appropriate technologies has to be in accordance with the local climatic conditions and the desirable load to be covered, and optimization should be based on the energy factor of such a system rather than the economic factor.

The next chapter will provide an innovative model for the simulation and optimization process of the energy aspect of RES hybrid projects.

Box 3 Summary of the simulation and optimization analysis of several RES projects.

4 OPTIMIZATION THEORY

This chapter is to describe an accurate energy optimization technique on the operation of a hybrid RES based autonomous system. This method will be based on an energy balance modeling among the main RES devices of such a project i.e. photovoltaic panels, wind turbines and buffering technologies. Regarding the offered amount of energy by the environmental potential to cover a specific desirable electric load, optimization of the simulated system's operational parameters is of primary interest. The produced "green" energy by the several eco-friendly technologies will be considered as the incoming energy of the presented theoretical model. As concern the desirable load in each time step for a simulated project and the remaining energy packs in the buffering technologies will be taken as decision variables which will be affected the optimization process of the simulated RES system. Furthermore the sensitivity analysis on several typical constraints will be conducted to identify the variations of incoming energy due to the operation of the system caused by the design parameters' of several RES based equipment embodied into a specific project.

4.1 BASIC PRINCIPALS ON THE ENERGY OPTIMIZATION OF AN AUTONOMOUS RES BASED POWER PLANT

Introduction – Previous optimization techniques incorporated in already existing simulation models use a simplified design of an RES based system which does not represent real-life combinations of different technologies. The most widespread optimization platform of HOMER used today uses buffering energy technologies as autonomous devices connected to the system's central dc bus. Moreover, to calculate the incoming "green" energy the platform uses average monthly values which do not accurately represent energy production because the simulation process is finalized using an hourly timetable for one whole year. The above design and the general approach cannot match a real-life scenario and reduces modeling practicability in real networks.

In order to be over passed the above dark spot during the simulation and optimization of a RES based system in the presented innovative model the buffering technologies during the design of a “green” project will be used as the connective link between the RES equipment and the desirable load. Also the optimization technique will follow an hourly basis model during a day. Throughout the presented optimization method the environmental potential will offer the total amount of electric energy to the battery bank and then it will be served to the system to cover the desirable electricity requirements according to an hourly timetable. Although the problem of an autonomous RES based project operation is typically multi-objective by nature none of the previous presented models has not presented a multi-objective energy optimization technique based on an accurate management of the offered energy effectively.

This chapter describes the development of a precise and realistic model on the optimization of autonomous RES based power plants. The mathematical modeling of a “green” project based on fundamental physics and an energy balance model is required to optimize the performance of hybrid systems.

Modeling – Initially the energy production of an eco-friendly hybrid RES system can vary according to several selected areas for its establishment due to the local meteorological data. The climatic conditions which represent the environmental potential are characterized by several dynamic variables which affect the operation of a “green” project under an unpredictable way. For this reason these variables will be considered as constant parameters for each different study location for a project which is going to be established.

The production of the electric energy according to the installed RES equipment of a system has been analytically described in Section 2.1 and is based on fundamental physics which can be considered as multi-reported in several research studies through the previous years. Here the main scope is the maximization of the energy flow throughout an established real-life RES project and at the same time the minimization of the appropriate applied eco-friendly capacity’s equipment in order to be reduced the NPC of the system. In this part of the present thesis the conditions under which a hybrid RES based system has to operate in order to be considered as optimized will be described throughout a new mathematical model in order to be succeeded the simulation and optimization process of an established project.

Initially, it is essential to describe the schematic diagram of the RES based hybrid system in Figure 4.1 which shows the combination of different devices in a real-life scenario. This diagram helps describe the energy balance and the general law more accurately which describes an optimized system from the energy point of view.

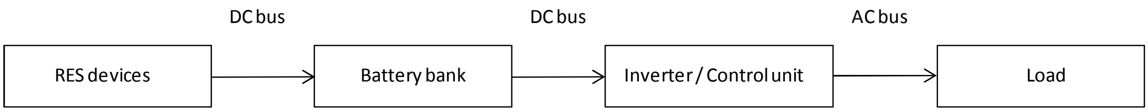


Figure 4.1 A real-life autonomous RES based hybrid scenario.

RES technologies take advantage of climatic conditions and produce the electrical energy, through buffering technologies, to cover the desirable load of an established unit. The calculation of the offered energy pack per device was described in Chapter 2 and the sum constitutes the total available energy and the remaining energy in the battery bank. Therefore, the energy pack which is traded through the DC bus can be described by Equation 4.1:

$$E_{available\,DC} = \left(1 - n_{Ohm}\right) \cdot E_{tot.\,prod.} + E_{remaining},$$

where n_{Ohm} is the factor describing the losses due to Ohm's law (%), $E_{tot.\,prod.}$ is the energy produced by the RES devices (kWh), and $E_{remaining}$ is the remaining energy in the storage bank between the time steps during the simulation of an RES project.

Equation 4.1 The total available energy offered by the devices through the DC bus for energy coverage.

The available energy, as described by equation 4.1, will sustain a reduction due to the efficiency of the inverter. This can be considered as constant according to the equipment chosen for use in each project. Data for this constant can be obtained from the manufacturer's manual and therefore Equation 4.1 becomes to Equation 4.2 and now describes the total amount of energy traded to cover the desirable load.

$$E_{available\ AC} = n_{inv.} \cdot E_{available\ DC}\ ,$$

where $n_{inv.}$ is the efficiency factor of the inverter (%), $E_{available\ DC}$ is the total amount of energy produced by "green" devices (kWh) including the storage bank.

Equation 4.2 The total available energy traded by the AC bus for energy coverage.

At this point of the optimization analysis it is essential to present a critical parameter that plays the most important role when deciding whether an RES based project has been optimized. This is the upper limit of stored energy remaining in the buffering technologies and is described by Equation 4.3:

$$E_{cap.\ AC} = n_{inv.} \cdot E_{cap.\ DC}\ ,$$

where $n_{inv.}$ is the efficiency factor of the inverter (%), and $E_{cap.\ DC}$ is the total amount of stored energy (kWh) according to the manufacturer's characteristics.

Equation 4.3 The upper limit of the buffering technologies in the system.

Following the above analysis it must be determined if the established RES technologies can cover the desirable load of the simulated project. Therefore, the application of the Equation 4.4 in each time step of the simulated project is essential. If the system is satisfied by part (a) of Equation 4.4 then the hourly desirable load is covered. If not, part (b), the system can be characterized as not optimized. The right side of Equation 4.4 represents the Depth of Discharge of the battery bank at which point the system shuts down and the storage bank finalizes its operation process. This value can be obtained from the manufacturer's specifications for each battery bank.

(a) $$E_{available\ AC} - Load \geq 0.4\ E_{cap.\ AC}$$

(b) $$E_{available\ AC} - Load < 0.4\ E_{cap.\ AC}$$

where $Load$ is the desired electrical load (kWh).

Equation 4.4 The law for the coverage of the desired load.

The last part of this optimization theory will be finalized through Equation 4.5. The equation has two parts and a simulated scenario can follow either part. To proceed to the system's final check, the scenario must obey part (a) of the equation 4.5.

(a) $$E_{available\ AC} - Load > E_{cap.\ AC}$$

(b) $$0.4\ E_{cap.\ AC} < E_{available\ AC} - Load \leq E_{cap.\ AC}$$

Equation 4.5 The basic law for the optimization theory.

A simulated project that satisfies part (a) of Equation 4.5 cannot be characterized as optimized even if the desired load can be covered. Such a system is considered as oversized with no optimized financial results for a future investor because certain amounts of energy are wasted by dispersion into the environment or stay unexploited in an autonomous system. A system that fulfills part (b) of equation 4.5 can be characterized as fully optimized. This system can cover the electrical requirements and at the same time the excess energy do not exceed the specific amount which can be stored in several buffering devices. The optimal condition of a simulated project is presented when the equal symbol of Equation 4.5 (b) can be satisfied for each simulated hour during a whole year.

The above optimization technique is based on the energy balance during the operation of an autonomous hybrid system which embodies an objective function containing all the essential meteorological data and the specifications of the ongoing established RES technologies of the project. The energy balance model is based on Equations 4.1 and 4.2, and can be described by Equation 4.6.

$$\text{Energy Balance} = n_{inv}\left[\left(1 - n_{Ohm}\right)\cdot E_{tot.\ prod.} + E_{remaining}\right] - Load,$$

where $Load$ is the load to be covered (kWh) according to the project's requirements.

Equation 4.6 The energy balance model.

The above expression can be characterized as the central objective function which characterizes the energy balance of a simulated RES based project and this has to be optimized through the values' limitation as they arise by the nullification of its first derivatives and are presented by the Equation 4.5. The analytical expression and parameters participated in the central objective function of a simulated RES project are given in Equation 4.7.

$$\text{En. Bal.} = n_{inv}\left\{(1\text{-}n_{Ohm})\left[n_{turb}n_{gen}\rho g h_{eff}Q + 0.2A^{2}1.23u^{3} + P_{STC}f_{PV}\left(\frac{\overline{G_T}}{G_{STC}}\right)\left[1 + a_P\left(T_C - T_{C,STC}\right)\right]\right]time + E_{remaining}\right\} - Load$$

Equation 4.7 The basic objective function of the energy balance modeling the optimization process.

From Equation 4.7 is can be seen that all the factors referring to meteorological data can be considered as constants at each time step and cannot interfere in the climatic conditions. For this reason, the crucial variables for the optimization of the simulated project are the parameters concerning the accurate design of the chosen technologies, such as $h_{eff}(m)$, $A(m^2)$, and $P_{STC}(kW)$. Finally, the objective function presented in Equation 4.7, contains a problematic section which is based on the accurate modeling of the battery bank in order to calculate the $E_{remaining}$ at each time step. The process of calculating this value at each time step constitutes an innovative approach to system modeling and will be described in Chapter 5 also presenting an experimental process that can validate the theoretical results.

Chapter 4 investigates a technique for the optimization of hybrid RES based stand-alone systems from the energy aspect.

The main aim is to model the energy balance during the operation of RES technologies in order to cover the electrical needs of a simulated project. This optimization technique contains some problematic points concerning the energy remaining in the buffering technologies and these will be embodied into an innovative simulation platform which will be presented in Chapter 5. The presented optimization technique in Chapter 4 can be characterized as an innovative approach to system modeling because the already existing simulation tools are based on the financial optimization of a “green” system.

Box 4 Summary of the optimization theory.

5 INNOVATIVE APPROACHES TO SIMULATION TOOLS

The present section of this thesis is based on the feasibility of stand-alone hybrid systems based on photovoltaic and wind energy in combination with an electrochemical storage bank. Initially, this study will focus on the design and operation of an autonomous hybrid system under real-life meteorological conditions which can simulate several loads assumed to cover the electricity demands of small buildings. Experiments will also be performed on the coverage of annual loads of a typical house, a typical country house and a small company, to prove the feasibility of stand-alone systems. A RES project established to operate under real-life conditions will be additionally simulated on a yearly basis using the HOMER software platform to determine real-time results. The above analysis will reveal that HOMER software cannot successfully simulate the operation of such a system. Finally, a new mathematical model will be designed in order to produce similar results to those produced from the experimental process.

5.1 DESIGN AND IMPLEMENTATION OF AN OFF-GRID HYBRID RES BASED LAB-SCALE POWER PLANT FOR ELECTRICITY PRODUCTION

Background - Several parameters must be taken into account when working on the design and implementation of a hybrid stand-alone RES based system, for the production of electricity that covers a specific desirable load on a daily basis. Various studies conclude that hybrid renewable electrical systems in off-grid applications can be feasible, especially in isolated areas, even when their character is not totally eco-friendly when supported by diesel generators, to cover primary peak load or when the environmental potential is generally low (Elhadidy 2002, Muselli et al. 1999, McGowan & Manwell 1999, Vera Gutierrez 1992). In addition, considering the local climate, one specific combination of different RES-based technologies can be more promising than another combination (Shaahid & Elhadidy, 2003).

To ensure a continuous power supply, despite the unavoidable fluctuations of the environmental potential, it is necessary to incorporate an intermediate energy storage system into any off-grid RES based design. The main characteristic of such a system during its operation, depending on the environmental potential, is that all RES based technologies supply "green" energy to the storage bank and this is offered continuously by the inverter to cover the desirable load.

Currently, the most common option for such buffering is electrochemical batteries, which are (a) efficient enough to be combined with renewable technologies, (b) have limited initial cost compared to other technologies for small investments, (c) provide continuous energy for several hours under stable voltage, (d) are without major safety issues, and (e) do not require a large, specially designed room for their installation in small-scale building projects (Peter & Euan 2008, Chang et al. 2009, Nirmal-Kumar & Garimella 2010, Leadbetter & Swan 2012). For these reasons, electrochemical batteries were used in this research.

Materials & Methods - To investigate the feasibility of stand-alone RES-based power plants, a laboratory-scale system was designed and established at the Department of Environmental and Natural Resources Management located in Agrinio, Greece. The system was built on the roof of a building where the university is housed in order to simulate real-life conditions of electricity "supply & demand". The specific system was constructed as follows: a Sovello photovoltaic panel at 12V with 205W theoretical peak power and an Air Breeze wind turbine at 12V with 300W peak power were combined with a storage bank comprising two Effecta deep-cycle batteries of 12V/55Ah connected in parallel. Furthermore, an Effecta DC-AC inverter, which can offer up to 350W continuous power, and a Sunlight Lighting controller/charger complete the system, as depicted in Figure 5.1. The specific equipment was chosen following an extensive study of their operational characteristics in order to be perfectly matched and to simultaneously cover the electrical needs of the experimental scenarios presented below. To finalize the experimental layout, several cables, fuses and gauges were used to indicate voltage and current at specified nodes of the circuit, thus permitting calculation of the electricity produced and consumed. To simulate several different AC loads on an hourly basis, different combinations of twelve valves were selected.

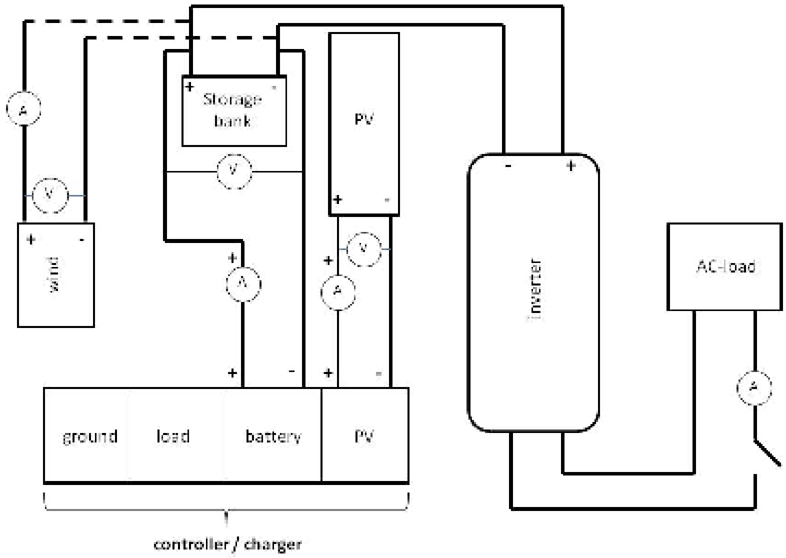


Figure 5.1 Schematic circuit diagram of the laboratory-scale system.

Three different loads were selected and are presented in Tables 5.1a, b & c. These loads are characteristic of the electricity requirements of a typical Greek 4-membered family house, a typical Greek country house for the same family, and a typical Greek small company. The latter was assumed to be a single building unit with offices equipped with A/C systems, lighting devices as well as PCs and framework computers. These loads generally stand for the majority of potential applications, and therefore adequately represent real-life scenarios. The desirable loads were produced by downsizing the real-scale loads presented in Tables 3.2a-c. In each case, the percentage of the downsizing was determined by the operational characteristics of the various devices and the restrictions arising from their engagement in the experimental process in order to cover the desirable load for each hour of one whole day. The differences between electrical loads through the seasons are due to the operation of devices necessary to cover human needs (e.g. air conditioning in summer). The period from September to May was considered unique regarding electricity demands, because there are no strong fluctuations in load requirements during this period. It should be noted that the primary load for a small company is increased during a typical August weekday, as Table 5.1c presents, even though the business is closed in this period. This has been included to cover unexpected visits of some employees to finalize projects with summer deadlines.

Time (h)	Consumption for September-May (kWh)		Consumption for June (kWh)		Consumption for July-August (kWh)	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
00:00-01:00	0.134	0.114	0.142	0.122	0.175	0.175
01:00-02:00	0.023	0.023	0.030	0.030	0.076	0.160
02:00-03:00	0.021	0.015	0.030	0.023	0.076	0.152
03:00-04:00	0.004	0.004	0.012	0.012	0.076	0.076
04:00-05:00	0.004	0.004	0.012	0.012	0.076	0.076
05:00-06:00	0.004	0.004	0.012	0.012	0.076	0.076
06:00-07:00	0.084	0.004	0.091	0.012	0.084	0.076
07:00-08:00	0.053	0.004	0.053	0.012	0.053	0.076
08:00-09:00	0.003	0.004	0.003	0.012	0.003	0.076
09:00-10:00	0.003	0.038	0.003	0.046	0.003	0.038
10:00-11:00	0.003	0.183	0.003	0.183	0.003	0.183
11:00-12:00	0.003	0.084	0.003	0.084	0.003	0.084
12:00-13:00	0.003	0.030	0.003	0.030	0.003	0.030
13:00-14:00	0.023	0.228	0.030	0.236	0.030	0.236
14:00-15:00	0.023	0.114	0.030	0.122	0.030	0.122
15:00-16:00	0.152	0.023	0.160	0.030	0.160	0.091
16:00-17:00	0.152	0.266	0.160	0.274	0.160	0.350
17:00-18:00	0.114	0.038	0.122	0.046	0.122	0.137
18:00-19:00	0.076	0.030	0.084	0.038	0.084	0.038
19:00-20:00	0.076	0.076	0.084	0.076	0.084	0.076
20:00-21:00	0.076	0.076	0.084	0.076	0.084	0.076
21:00-22:00	0.190	0.190	0.198	0.190	0.198	0.190
22:00-23:00	0.076	0.152	0.076	0.152	0.084	0.152
23:00-00:00	0.114	0.053	0.114	0.053	0.122	0.053

(a)

Time (h)	Consumption for September-May (kWh)		Consumption for June (kWh)		Consumption for July-August (kWh)	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
00:00-01:00	0.007	0.056	0.007	0.068	0.068	0.068
01:00-02:00	0.007	0.045	0.007	0.056	0.056	0.056
02:00-03:00	0.007	0.007	0.007	0.018	0.018	0.018
03:00-04:00	0.007	0.007	0.007	0.018	0.018	0.018
04:00-05:00	0.007	0.007	0.007	0.018	0.018	0.018
05:00-06:00	0.007	0.007	0.007	0.018	0.018	0.018
06:00-07:00	0.007	0.007	0.007	0.018	0.018	0.018
07:00-08:00	0.007	0.007	0.007	0.018	0.018	0.018
08:00-09:00	0.007	0.007	0.007	0.018	0.018	0.018
09:00-10:00	0.007	0.056	0.007	0.056	0.056	0.056
10:00-11:00	0.007	0.090	0.007	0.090	0.090	0.090
11:00-12:00	0.007	0.045	0.007	0.045	0.045	0.045
12:00-13:00	0.007	0.045	0.007	0.056	0.056	0.056
13:00-14:00	0.007	0.339	0.007	0.350	0.350	0.350
14:00-15:00	0.007	0.169	0.007	0.181	0.181	0.181

15:00-16:00	0.007	0.034	0.007	0.045	0.226	0.226
16:00-17:00	0.007	0.034	0.007	0.045	0.169	0.169
17:00-18:00	0.007	0.068	0.007	0.079	0.169	0.169
18:00-19:00	0.007	0.045	0.007	0.056	0.056	0.056
19:00-20:00	0.007	0.113	0.007	0.124	0.124	0.124
20:00-21:00	0.007	0.226	0.007	0.237	0.237	0.237
21:00-22:00	0.007	0.226	0.007	0.237	0.237	0.237
22:00-23:00	0.007	0.056	0.007	0.068	0.068	0.068
23:00-00:00	0.007	0.056	0.007	0.068	0.068	0.068

(b)

Time (h)	Consumption for September-May (kWh)		Consumption for June-July (kWh)		Consumption for August (kWh)	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
00:00-01:00	0.003	0.003	0.003	0.003	0.003	0.003
01:00-02:00	0.003	0.003	0.003	0.003	0.003	0.003
02:00-03:00	0.003	0.003	0.003	0.003	0.003	0.003
03:00-04:00	0.003	0.003	0.003	0.003	0.003	0.003
04:00-05:00	0.003	0.003	0.003	0.003	0.003	0.003
05:00-06:00	0.003	0.003	0.003	0.003	0.003	0.003
06:00-07:00	0.003	0.003	0.003	0.003	0.003	0.003
07:00-08:00	0.003	0.003	0.003	0.003	0.003	0.003
08:00-09:00	0.053	0.003	0.053	0.003	0.053	0.003
09:00-10:00	0.053	0.053	0.053	0.053	0.053	0.003
10:00-11:00	0.053	0.053	0.350	0.350	0.350	0.003
11:00-12:00	0.053	0.053	0.350	0.350	0.350	0.003
12:00-13:00	0.053	0.053	0.350	0.350	0.350	0.003
13:00-14:00	0.030	0.053	0.350	0.350	0.350	0.003
14:00-15:00	0.030	0.030	0.350	0.350	0.350	0.003
15:00-16:00	0.053	0.030	0.350	0.350	0.003	0.003
16:00-17:00	0.053	0.053	0.350	0.003	0.003	0.003
17:00-18:00	0.053	0.053	0.350	0.003	0.003	0.003
18:00-19:00	0.053	0.003	0.053	0.003	0.003	0.003
19:00-20:00	0.053	0.003	0.053	0.003	0.003	0.003
20:00-21:00	0.053	0.003	0.053	0.003	0.003	0.003
21:00-22:00	0.053	0.003	0.053	0.003	0.003	0.003
22:00-23:00	0.003	0.003	0.003	0.003	0.003	0.003
23:00-00:00	0.003	0.003	0.003	0.003	0.003	0.003

(c)

Table 5.1 Loads for a typical house (a), a typical country house (b), and a small company (c), for one day.

Experimental process - For each of the cases presented in Tables 5.1a-c, real-time measurements of voltage and current were taken every five minutes from the output of the RES-devices. By simply multiplying these two values, one can calculate the power provided to the system by the environmental potential. Thus, the average energy potential offered to the system by RES (i.e., solar and wind energy) can be calculated on an hourly basis. Moreover, given the desirable load on an hourly basis, a typical energy balance allows the calculation of excess energy and the unmet-load. To ensure maximum accuracy for each scenario, all the measurements included in the experimental process were repeated several times during selected days of the same season and with similar meteorological data.

a) Local meteorological data - Meteorological data were taken for several days throughout one year in order to adequately represent all possible weather conditions throughout the four seasons. The meteorological data for the specific location of the present project (Agrinio city, Western Greece) was provided by a local weather station established at the same area of the RES based project. The data recorded include the local temperature, wind velocity and solar radiation and are shown in Figure 5.2, Figure 5.3 and Figure 5.4, respectively.

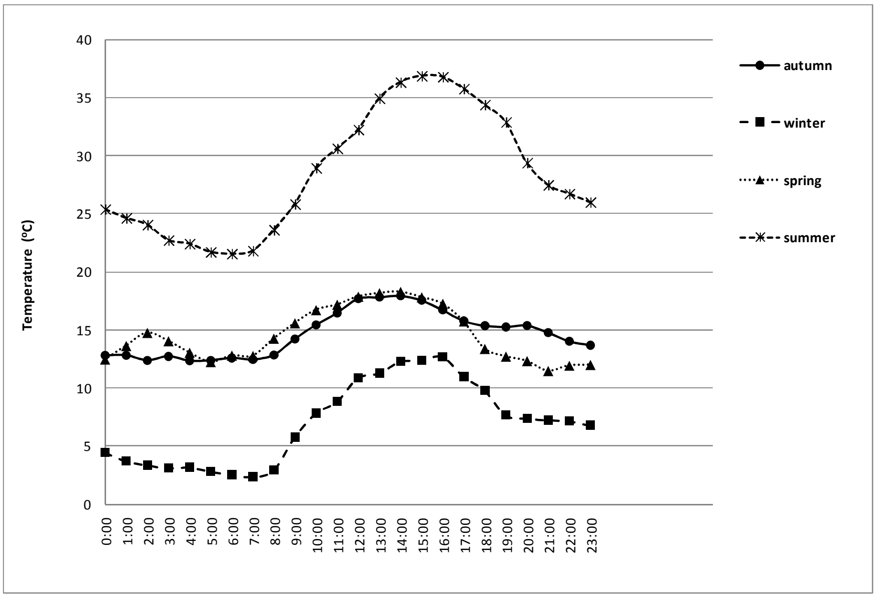


Figure 5.2 Temperature variation during a typical day of each season.

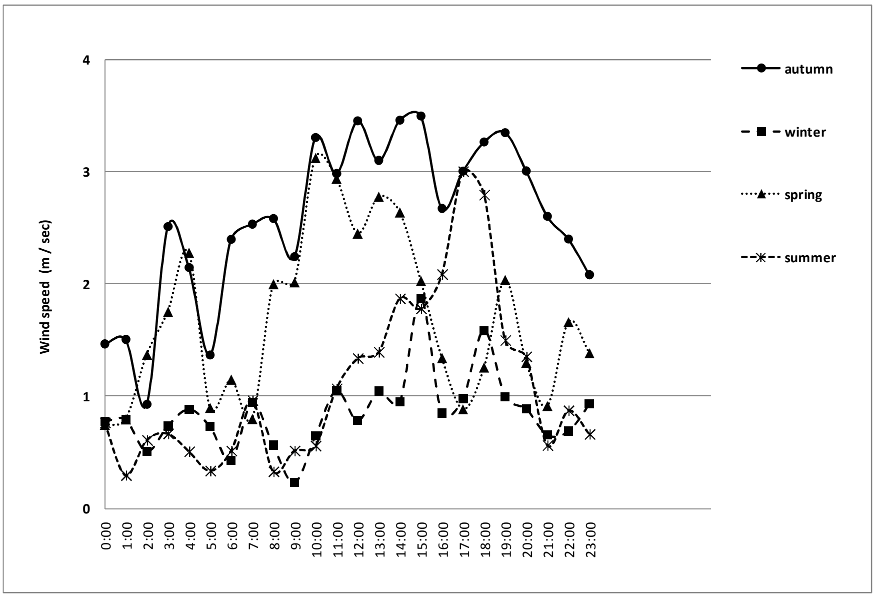


Figure 5.3 Wind speed variation during a typical day of each season.

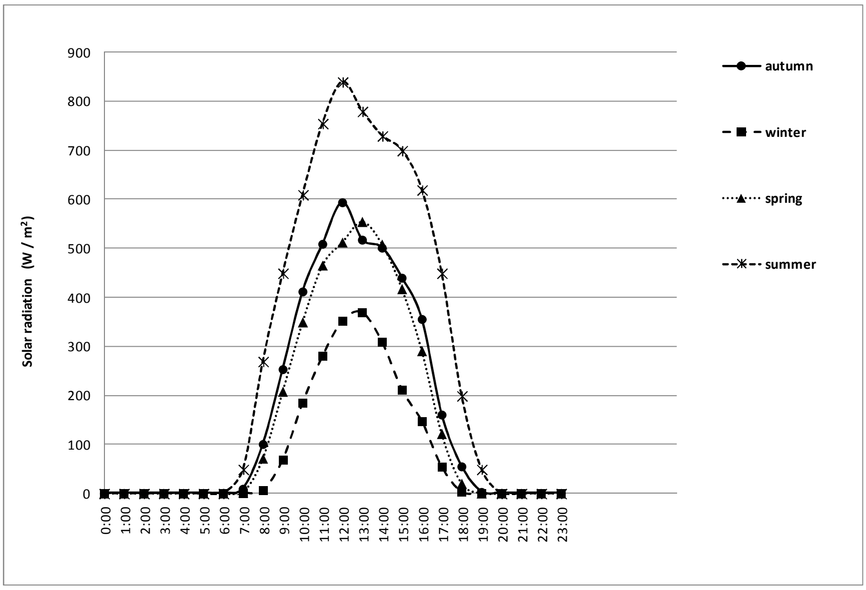


Figure 5.4 Solar radiation during a typical day of each season.

b) Correlation of State of Charge of a given battery with the measured voltage - One of the system's crucial parameters is the voltage of the battery bank that indicates its State of Charge (SOC) and Depth of Discharge (DOD) during its operational life. This voltage corresponds to the total capacity of the existing storage bank and its discharge rate when the desirable load is covered. The duration of each experiment was one year, during which the desired loads fluctuate.

To obtain an accurate correlation between SOC and voltage, it is necessary to investigate how voltage is correlated to SOC and how the remaining operational capacity of the battery can be predicted for a certain time period as a function of the desirable load to be satisfied during the same time period. Given the voltage at each time-step, an estimate of the charge level of a battery bank must also be determined.

The theoretical electric energy offered hourly by the energy storage bank (batteries) is 1.320 kWh (12V/55Ah). When the voltage exceeds 12V, the storage bank is considered fully charged and can provide 85% of the theoretical amount of stored energy to the system. This percentage practically represents the discharge efficiency of typical electrochemical batteries. Figure 5.5 presents the power offered per hour as a function of voltage. As shown, for voltage values over 12V, the power is assumed to be constant since the DC bus is active up to 12V. When the voltage is lower than 9.5V, the power is approx. 0.530 kW, i.e. 40% of the theoretical total capacity of the battery bank (DOD). Under this DOD value, the storage bank cannot provide sufficient energy to the system, whose demands have to be covered directly by the RES used.

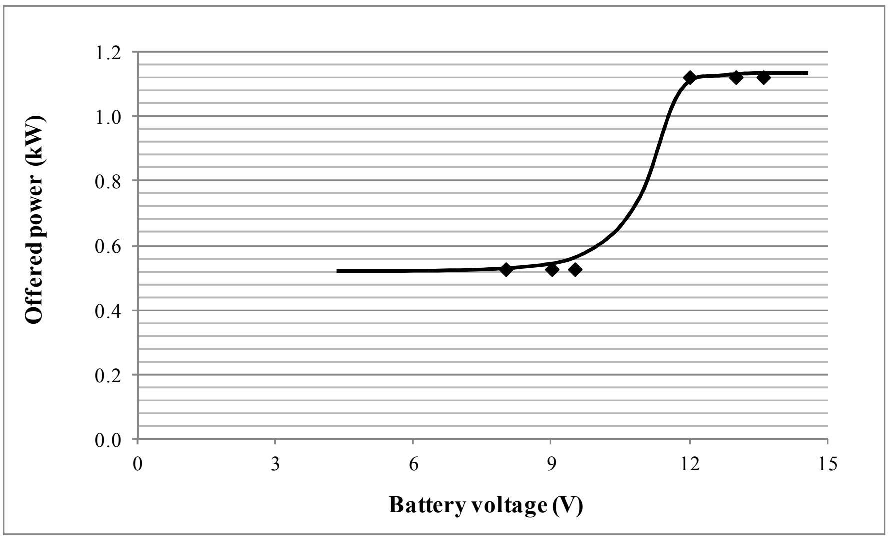


Figure 5.5 Energy offered by the battery bank as a function of voltage.

In the 9.5 to 12V range, the power offered is approximately fitted by a linear function as presented in Equation 5.1:

$$P = 0.238\,V - 1.729\,,$$

where, P is the power offered by the battery bank, and V is the voltage.

Equation 5.1 Power offered from a storage bank as a linear function of voltage in the useful operational area.

It is clear that the coefficients of the above equation are not dimensionless and stand only for the specific batteries used in this study; however they may be changed accordingly when other battery types are considered. These coefficients can be experimentally calculated through the inclination of the schematic diagram when the battery bank discharges under a stable load. During this process the voltage decreases and if the greatest value of the offered current is known the remaining power in the battery bank can be easily determined. Finally, SOC can be estimated for each battery bank by using simple arithmetic calculations.

Results and General discussion - Figure 5.6 presents the electricity requirements of a typical house during a typical autumn weekday as shown in Table 5.1a. This desirable load can be adequately covered by the hybrid system that can offer sufficient excess energy due to the high environmental potential of this season, and at the same time the electrochemical battery bank remains totally charged at the end of the day.

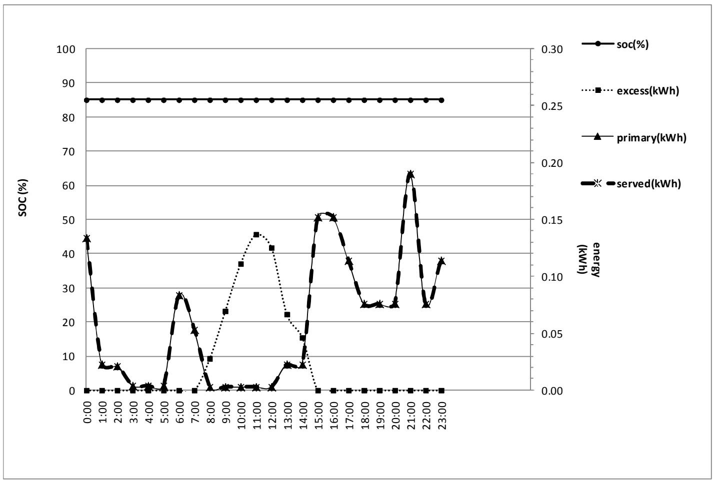


Figure 5.6 The typical house during a typical autumn weekday.

The electricity requirements that must be covered for the stable operation of a typical house are represented by the ‘primary’ load line. The ‘served’ line shows the final load that can be covered by the system, and the extra energy produced by the system is the ‘excess’ line. In Figure 5.6 the charge level of the battery is shown on the primary y axis and the other energy values are shown on the secondary y axis.

A similar result can be seen from the simulation of the typical house’s load during an autumn weekend. Figure 7 reveals that the average load fluctuates more because family members remain inside the building for more hours than in the summer. The system’s served load follows exactly the primary load, there is some excess, and after one day the electrochemical battery bank remains fairly highly charged (SOC appears to be approx. 70% of the total theoretical capacity).

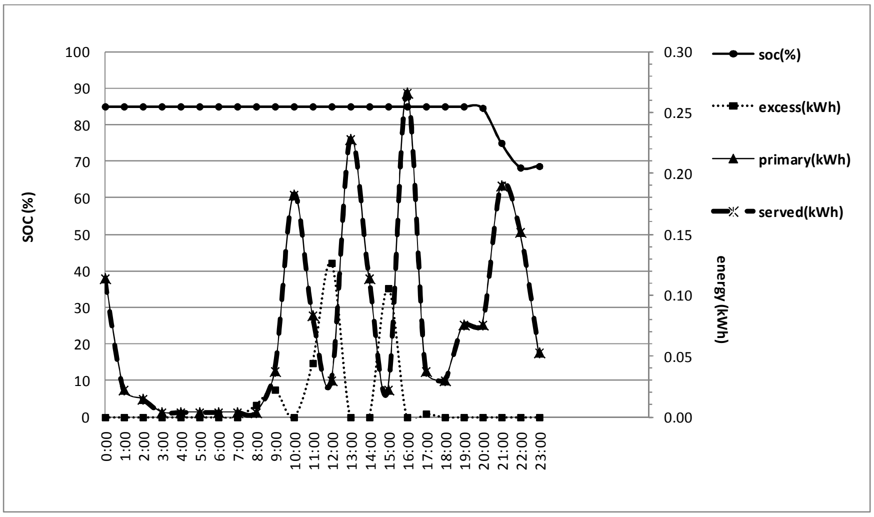


Figure 5.7 The typical house during a typical autumn weekend.

Figure 5.8 and Figure 5.9 present the response of the system to satisfy the electricity demands of a typical house during a weekday and weekend, respectively, under the low environmental potential of a typical winter period. The weekday’s primary load appears to be covered fully by the energy offered by the RES-based layout and the SOC remains over 80% at the end of the day (Figure 5.8). However, during a typical weekend day the desirable load cannot be covered fully and the system is out of order for the last 3 hours of the day (Figure 5.9).The small amount of excess energy occurring during the day is not enough to support the system (Figure 5.9). Furthermore, SOC seems to be approx. 58%, which does not constitute the lower limit of the battery charge level, but emerges from the operation of the inverter that cannot operate under the value of 10.5V.

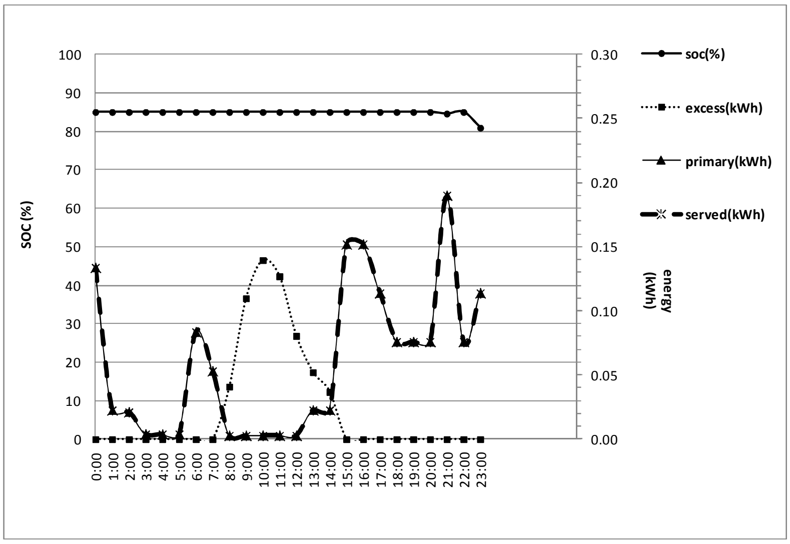


Figure 5.8 The typical house during a typical winter weekday.

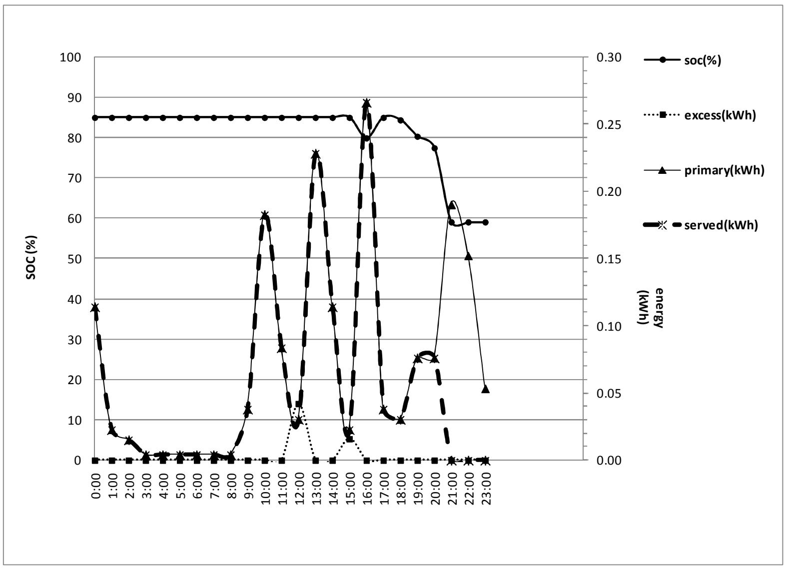


Figure 5.9 The typical house during a typical winter weekend.

Concerning a typical spring period, the environmental potential is almost the same as during autumn, characterized mainly by sunny days with fluctuations of solar radiation. Therefore the behavior of the established system to cover the load of typical house during a typical weekday or weekend will be similar to that of the autumn period. This assumption is verified by Figure 5.10 and Figure 5.11 for a typical weekday and weekend, respectively.

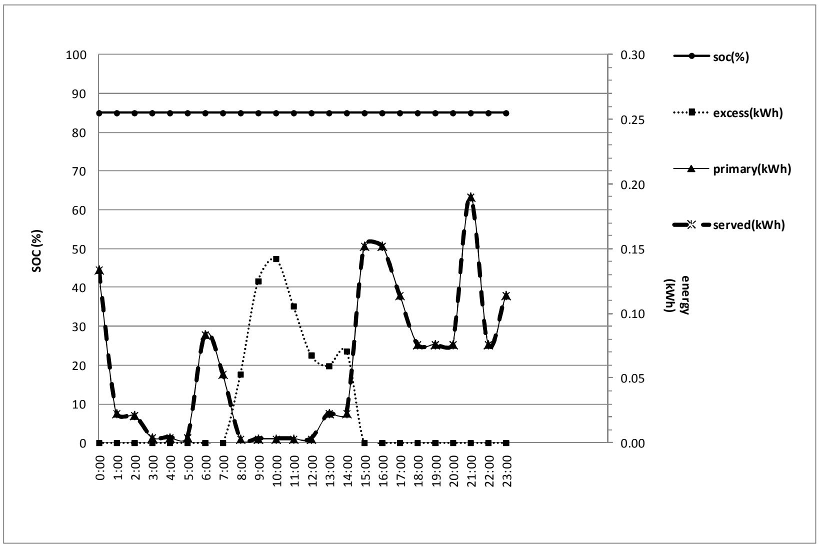


Figure 5.10 The typical house during a typical spring weekday.

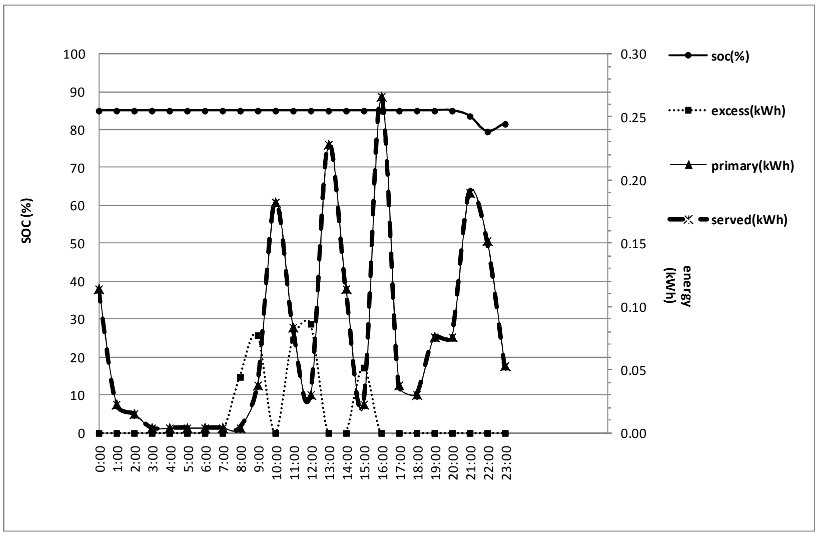


Figure 5.11 The typical house during a typical spring weekend.

Finally, the results for the summer period are presented in Figure 5.12 and Figure 5.13. During this period electricity requirements are increased due to extensive air conditioning use, and four different loads must be simulated to obtain a clear view of the system's coverage abilities. The primary load is covered by the served load and the batteries, whose SOC is high. It is important to distinguish the behavior of the system between the month of June and the July-August period.

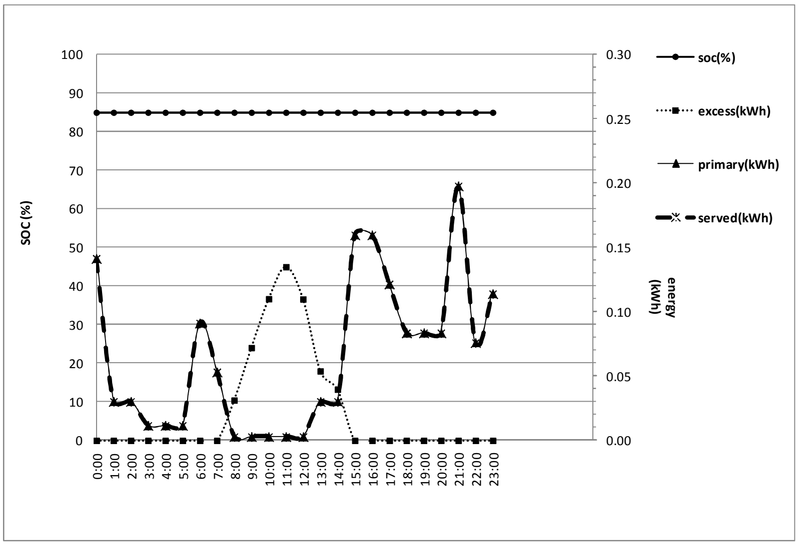


Figure 5.12 The typical house during a typical June weekday.

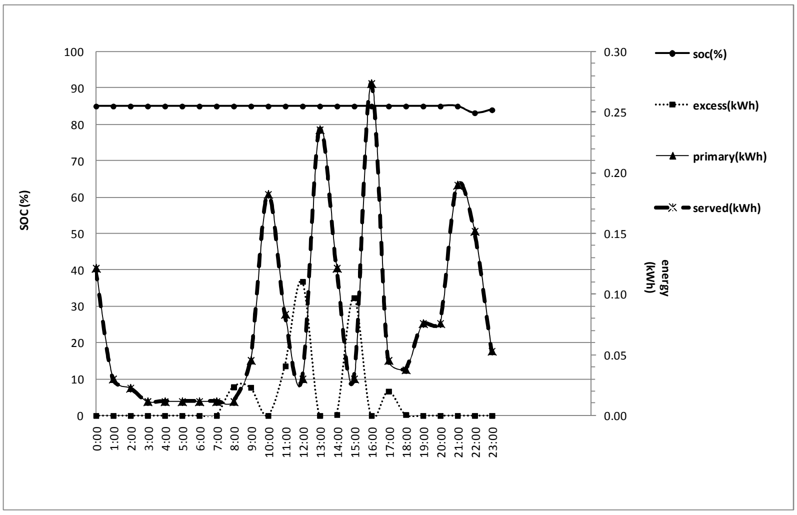


Figure 5.13 The typical house during a typical June weekend.

The majority of Greek citizens take vacations in July-August, thus the relative loads for both weekdays and weekends are significantly different (see Table 5.1a). Figure 5.14 verifies that the weekday load of the typical house is fully covered during the July-August period. However, a similar situation is not observed for the weekend load where the electricity requirements are increased. Therefore, the served load cannot satisfy the primary load and the system becomes out of order early in the afternoon (Figure 5.15).

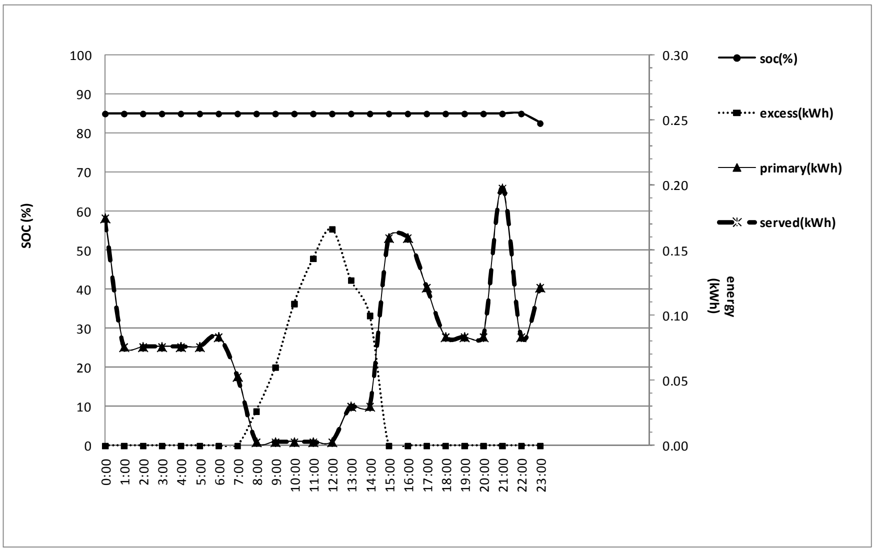


Figure 5.14 The typical house during a typical July-Aug weekday.

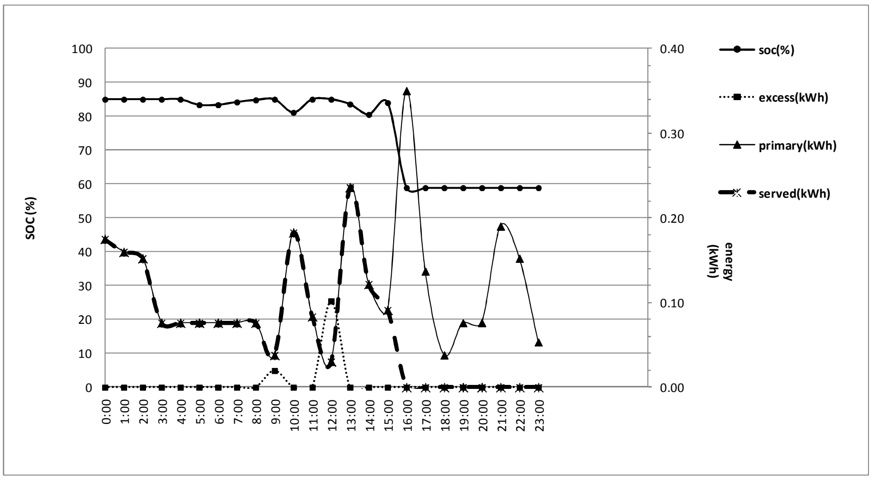


Figure 5.15 The typical house during a typical July-August weekend.

The simulation of a typical country house follows. The electrical needs of a typical country house during autumn, winter and spring fluctuate less than those of the typical house. This is in contrast to the summer months, when loads are usually higher. The system's behavior for the coverage of a typical weekday and weekend load of a typical country house in winter are shown in Figure 5.16 and Figure 5.17.

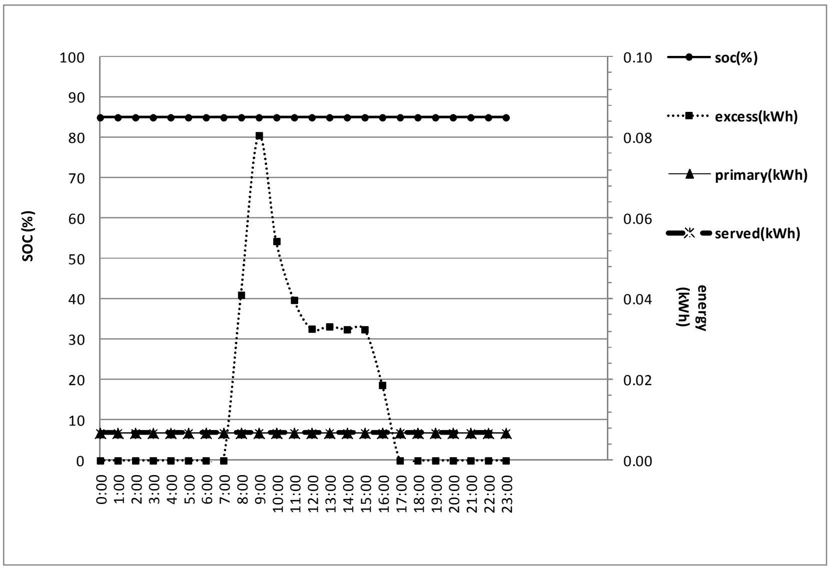


Figure 5.16 The typical country house during a winter weekday.

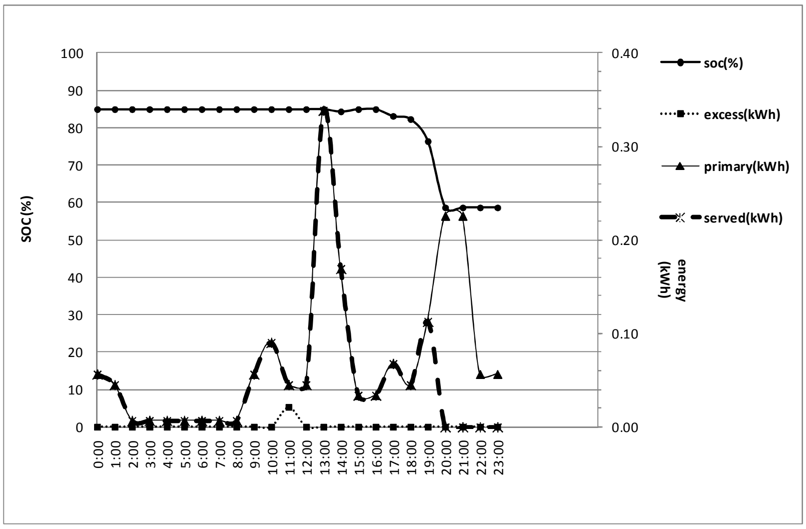


Figure 5.17 The typical country house during a winter weekend day.

During a typical weekday from September to May the desirable loads are fully covered, however, the served load is not able to satisfy the demands for the last four hours of a typical weekend day. This result is not observed during autumn and spring when demands can be adequately covered by the combination of RES and battery bank. The above observation is further strengthened by results presented in Figure 5.18 for the autumn period, where the same loads (Figure 5.16 and Figure 5.17) are fully covered and the SOC is fairly high (over 70% of its theoretical capacity).

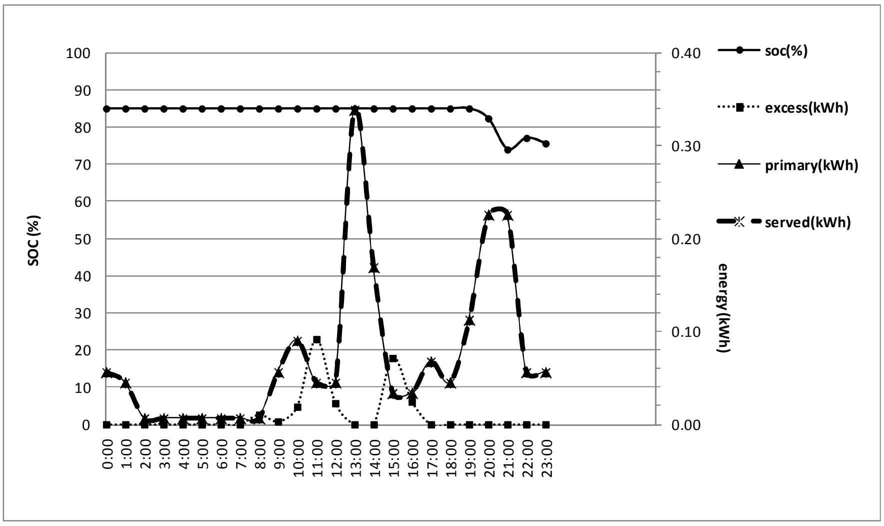


Figure 5.18 The typical country house during a typical autumn weekend day.

Regarding the month of June (working period), the needs of a typical country house during a weekday (Table 5.1b) are the same as the spring, autumn and winter seasons, thus the system's behavior can be represented by Figure 5.16. Moreover, although weekend loads are higher, they are satisfied with less excess and an almost fully charged storage bank (Figure 5.19). Finally, the typical weekday needs during the period of July-August cannot be covered by the experimental system which is deemed out of order from early afternoon to the end of the day (Figure 5.20).

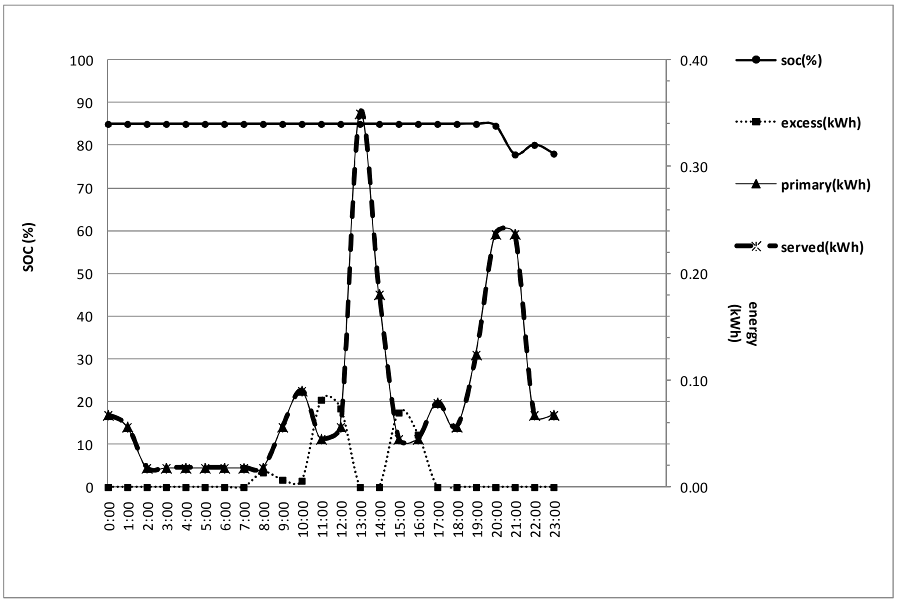


Figure 5.19 The typical country house during a June weekend.

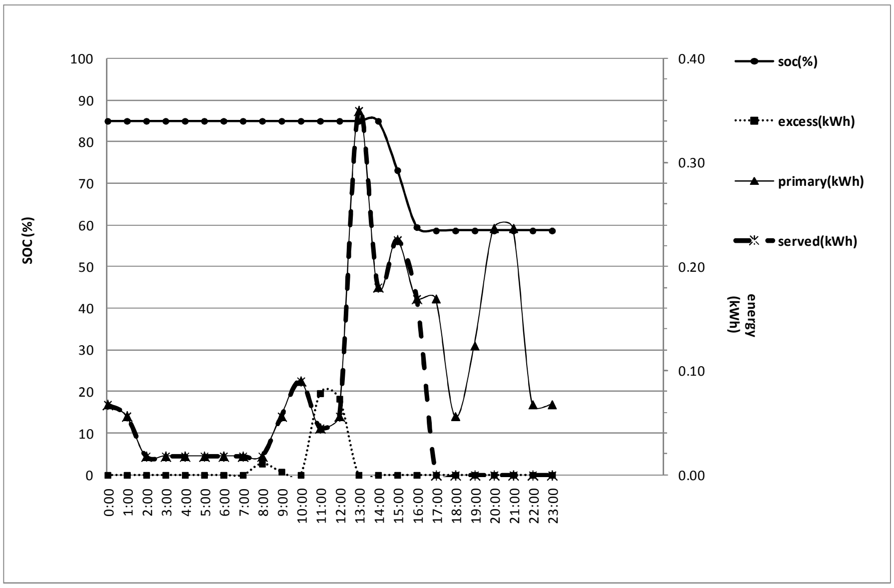


Figure 5.20 The typical country house during a typical July-August weekday.

In contrast, the system can fully cover the weekend load demands for the same period as shown in Figure 5.21. For the sake of completeness, the electricity requirements of a small company, comprising only offices without huge consumptions, were also simulated. In this case, the desirable loads are high for a certain time period each weekday and are otherwise constant at a very low value (Table 5.1c). Concerning the September to May period, the required load can be fully covered by the experimental system.

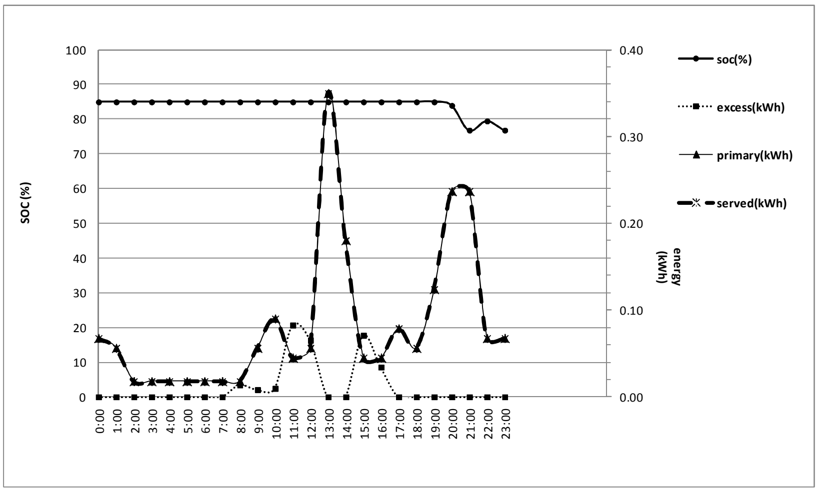


Figure 5.21 The typical country house during a typical July-August weekend.

The system's behavior during a typical weekday and weekend, as shown in Figure 5.22 and Figure 5.23 respectively, is more or less constant, presenting very low variations of excess energy due to weather conditions, especially in autumn and spring.

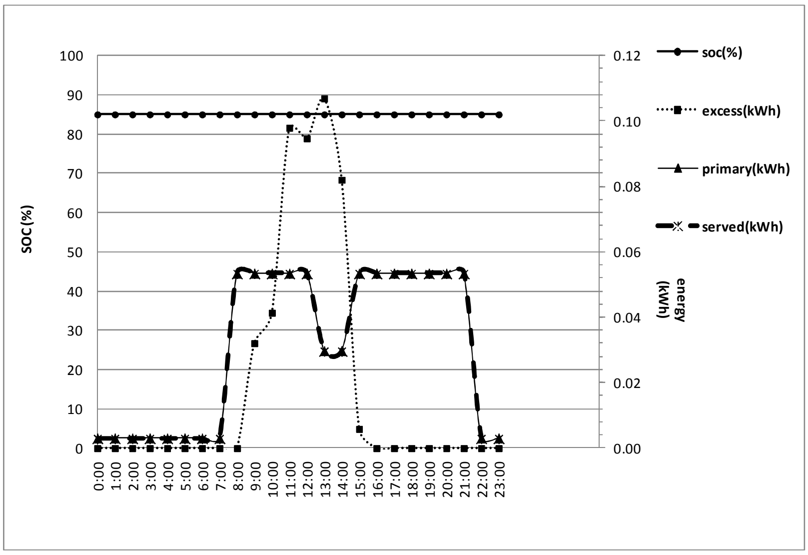


Figure 5.22 The typical company during a typical weekday for the September-May period.

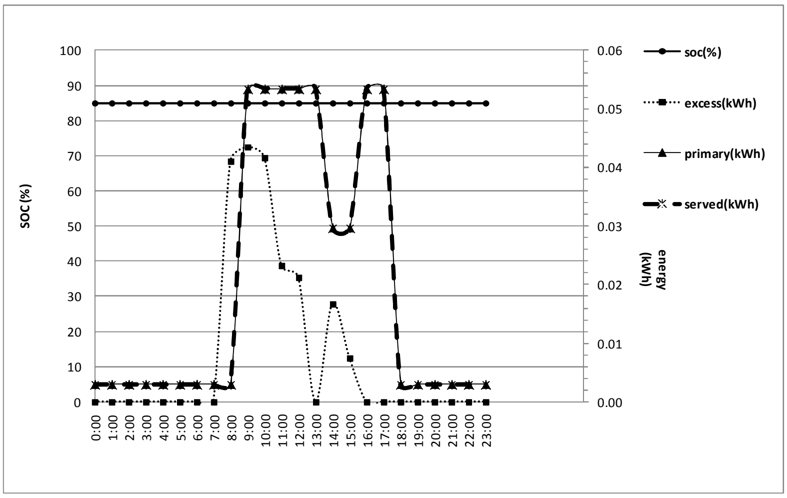


Figure 5.23 The typical company during a typical weekend for the September-May period.

It is worth mentioning that the daily electrical requirements of a typical small company during summer are 0.350 kWh (Table 5.1c) due to the operation of air conditioning units, and therefore this is the peak that the established system must cover. Under these conditions the system cannot satisfy either weekday or weekend demands, and is deemed out of order by early afternoon (Figure 5.24 and Figure 5.25). Finally, as the daily loads during an August weekend are constant and fluctuate the least compared to the other two simulated cases (0.003 kWh, see Table 1c), they can be fully met while SOC reaches 85% (Figure 5.16).

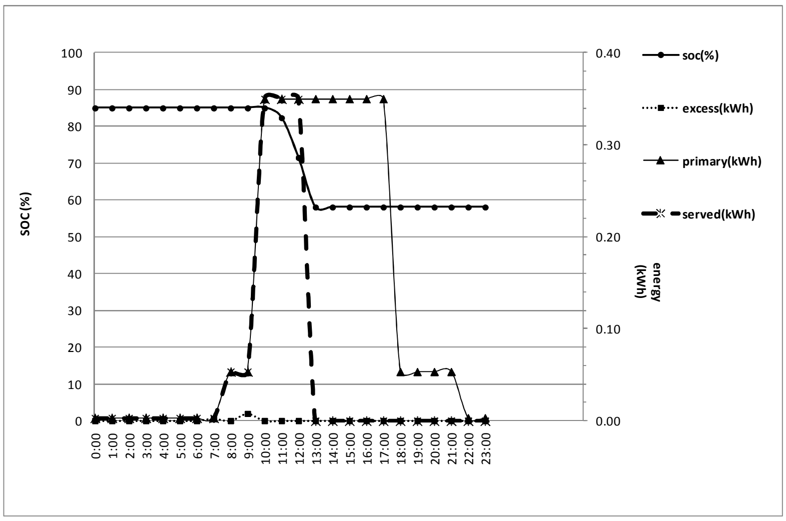


Figure 5.24 The typical company during a typical June-July weekday.

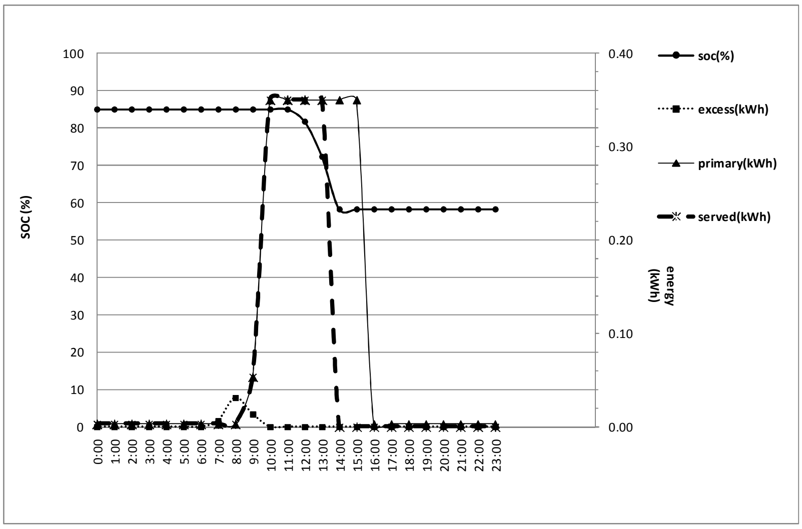


Figure 5.25 The typical company load during a typical June-July weekend.

The only notable difference is the production of a greater energy excess due to the high environmental potential, although this has no significant influence on the behavior of the hybrid system.

General conclusion -A laboratory-scale off-grid RES based power plant was built to examine the feasibility of such systems from an energy point of view. A photovoltaic panel with a wind turbine was used as the primary energy source, and a deep-cycle battery bank was chosen for intermediate energy buffering. The correlation between SOC and battery voltage was determined and allowed the characterization of the storage bank capacity. Three different case-studies characterized by different loads were simulated on an annual basis.

The first simulated scenario refers to the coverage of the annual electricity needs of a typical house. During a typical weekday and weekend in autumn and spring, the desirable electricity load of the house is fully covered by the system. A notable energy excess is produced, and battery SOC does not fall below 68%, **which is sufficient for the system's continuous operation**. For the simulated winter period, the served RES-produced energy can meet the primary weekday load but not a typical weekend day where 87.5% of the total hours can be satisfied due to the operational restrictions of the inverter. Finally, during June, the system can fully cover the desirable electricity requirements for a typical weekday and weekend day. Similar results were observed in the July-August period for weekday loads, but during a weekend day when loads fluctuate greatly, the system is deemed out of order from early afternoon. Therefore, it can be concluded that the hybrid system can cover the electricity requirements of a typical house for 344 days of a whole year (95.5%), which is an impressive result for a stand-alone eco-friendly system.

The second simulated scenario (typical country house) was also successful. The desirable load (as presented in Table 5.1b) is almost fully satisfied during a typical weekday and weekend day in the September-May and June periods. One situation where the experimental system cannot fully meet load demands is a typical weekend day in winter where the provided energy can satisfy the electrical needs of only 20 hours per day. Finally, in July-August the load of a typical weekend day is fully covered. This is in contrast to a typical weekday of the same period where just 70.8% of the total amount of hours can be covered by the system per day. It can be concluded that load demands can be fully met by the RES based technologies for **316 days of the year (87.7%)**. This number could be improved by better management of excess energy during winter when the load is stable for most of the day.

Finally, the coverage of the annual load of a small company (offices) was also simulated. During autumn, winter and spring the desirable loads can be fully covered. The second period of June-July presents interesting results since energy-wise only 14 of the 24 hours of one day (58%) can be satisfied. This is because the peak primary load is extremely high for the experimental system to cope with (see Table 5.1c) as the wind turbine has limited contribution due to low local wind potential. Therefore, the photovoltaic panel and battery bank combination becomes the main source covering the primary load. Similar behavior is observed during a typical August weekday, in contrast to a weekend day when the load is constant and can be totally covered by the system (Figure 5.16). In general, the requirements of a small company can only be met for 278 days (77.2%) of the year.

5.2 HOMER VS A NEW MODEL FOR THE OPERATION OF AN RES BASED HYBRID STAND-ALONE SYSTEM

Background - Many theoretical studies have been published on the design and simulation of hybrid RES based systems. These studies have used several mathematical algorithms since forecasting the performance of a potential RES based system in a specific location is crucial before its construction. A reliable forecasting tool could be extremely useful, especially for investors on projects with a totally eco-friendly character. The most widely used software package dealing with the simulation and optimization of hybrid systems and that includes financial considerations is HOMER (Bernal-Agustin & Dufo-Lopez, 2009, http://www.nrel/gov/HOMER).

By using HOMER, Dalton et al. (2009) showed that diesel generators used in small- and medium-scale tourist accommodation in remote locations can be replaced by RES based totally eco-friendly technologies with equivalent financial and energy results. An extensive parametric study using HOMER on the electrification of an ordinary house in Canada with an energy consumption of 25 kWh/day, reveals that the hybrid wind-diesel-battery system from which the house was fed, can be replaced by a totally "green" system with more promising results (Khan & Iqbal, 2005). Furthermore, various research studies on on-grid systems have been also finalized using HOMER software. The software appears to generate adequate results for energy production and operational performance of several projects (Bekele & Tadesse 2012, McHenry 2012a, 2012b, Ashourian et al. 2013).

The major drawback characterizing all autonomous RES based systems is that the environmental energy potential is quite unpredictable therefore temporary energy storage is crucial to provide an uninterruptable energy supply, especially for stand-alone RES based systems. Additionally, the storage bank stabilizes the operational characteristics of the local micro-grid that supplies energy to all the AC devices of the project. The most widely used technology for energy storage in hybrid RES based systems is electrochemical batteries as they are efficient enough to be combined with renewable technologies. These batteries also have limited initial costs (compared to other technologies), provide continuous energy for many hours during the day, and do not have serious safety issues (Peter & Euan, 2008). An accurate mathematical model embodied in a software simulation tool should be developed to describe batteries as energy buffers in off-grid systems. The modeling of an electrochemical battery bank was described in Section 5.1 and was achieved using an experimental layout. The above process determined that the most crucial element of an established system is the storage bank.

In the present section, the RES based hybrid system of Section 5.1 will be simulated in the HOMER platform to investigate the accuracy of the theoretical approach compared to real-life operation. Potential weak points of the theoretical process incorporated into HOMER are examined in detail. We also present a new mathematical model used to forecast the operation of stand-alone RES based hybrid systems.

Simulation of the hybrid system using HOMER - The laboratory-scaled hybrid system was simulated in the HOMER platform under a similar combination of RES-devices that comprised a 205W theoretical served peak power photovoltaic panel, a 300W peak power wind turbine, and a storage bank of two 55Ah electrochemical batteries with a parallel connection. For the theoretical simulations, mean monthly local meteorological data were provided by the same local weather stations as those during the experimental process. Data was taken for specific periods of one year as the HOMER platform uses averaged meteorological values to calculate the environmental potential of each time-step (Figure 5.26).

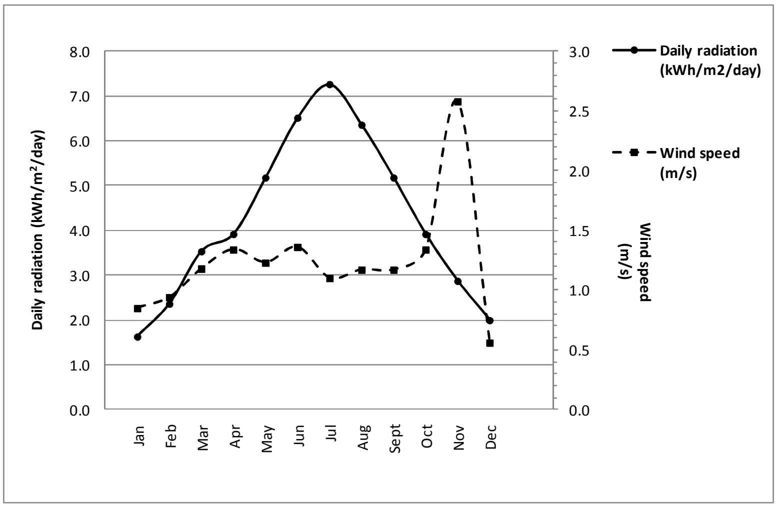
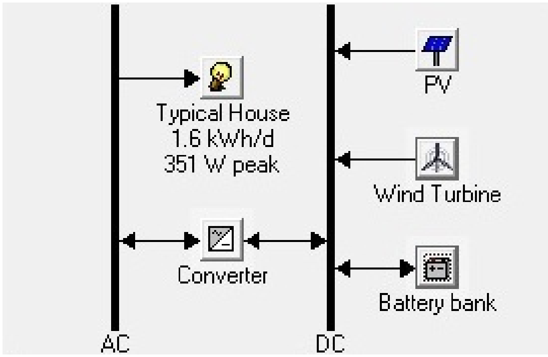
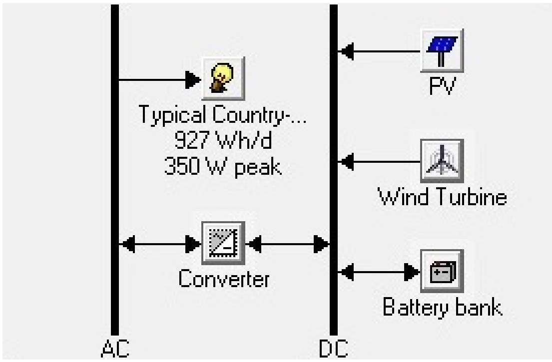


Figure 5.26 Averaged annual meteorological data.

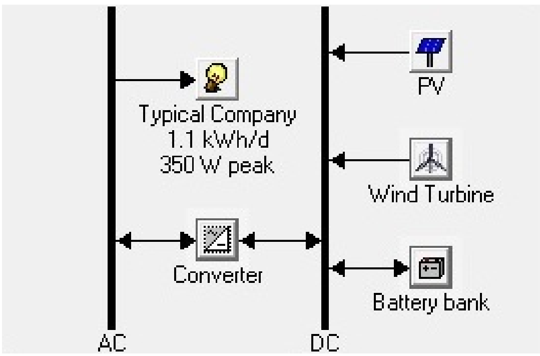
The RES based system was designed in HOMER using the same operational requirements as in the experimental process to cover the loads of a typical house, a typical country house, and a small company as shown in Figures 5.27a-c, respectively.



(a)



(b)



(c)

Figure 5.27 The three simulated scenarios: (a) typical house, (b) typical country house, and (c) typical small company.

The desirable loads were presented in detail in Tables 5.1a-c, and have been produced by downsizing the actual building-scale loads in accordance to the restriction in energy production caused by the operational characteristics of the devices used. Regarding loads for the typical house, a common weekday in autumn can be covered only during midday hours or early afternoon when the environmental potential is at a maximum (Figure 5.28).

Moreover, during the same period of the year but during a typical weekend, the desired electricity demands can be met for only a few hours when rated at low levels, as Figure 5.29 presents. In addition, the battery SOC cannot exceed 60%, indicating that the storage bank is almost empty during the whole process. Identical behavior can be observed in spring and winter months because the environmental potential is equivalent to or lower than that of autumn.

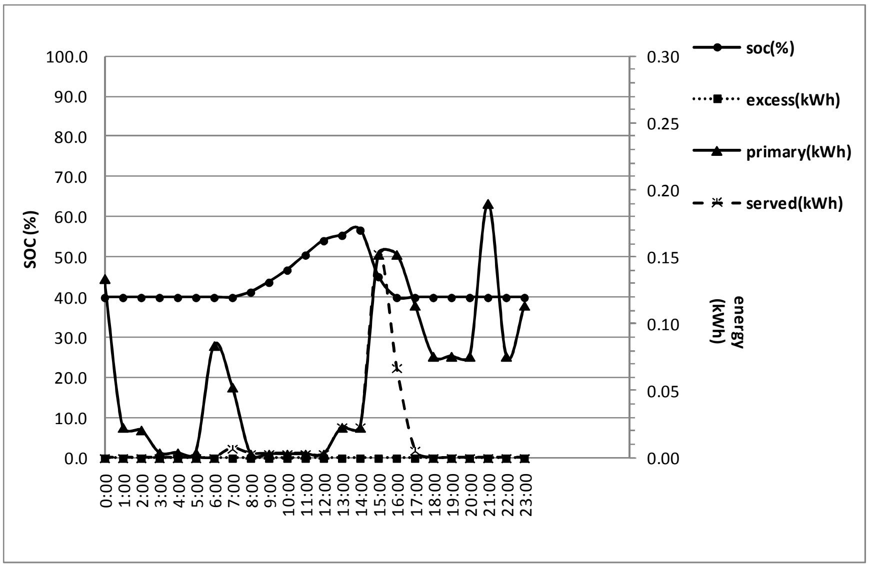


Figure 5.28 Typical house for a weekday during autumn.

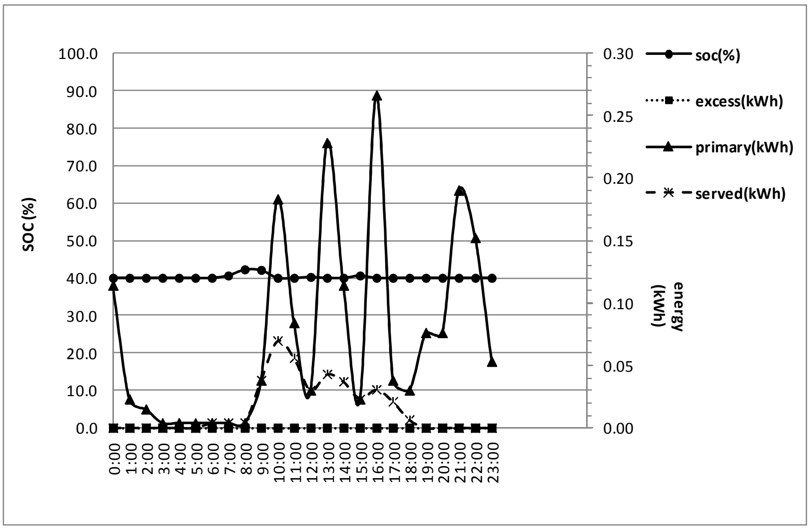


Figure 5.29 Typical house for a weekend day during autumn.

Summer has been separated into two periods; June and July to August, according to the different activities taking place (see discussion in section 5.1). Therefore, the simulations here commence from a typical weekday or weekend in June, as Figure 5.30 and Figure 5.31 show respectively, where the electricity demands cannot be satisfied by the present system.

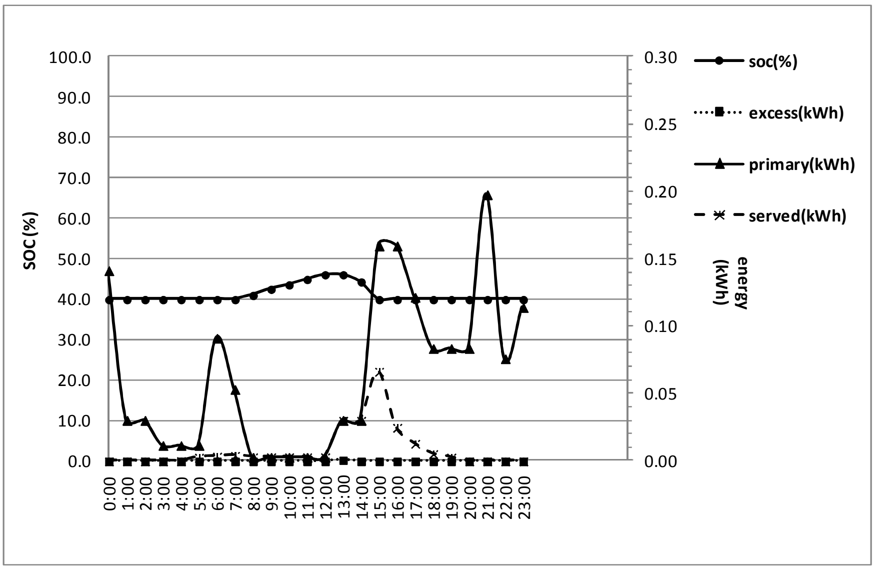


Figure 5.30 Typical house for a weekday in June.

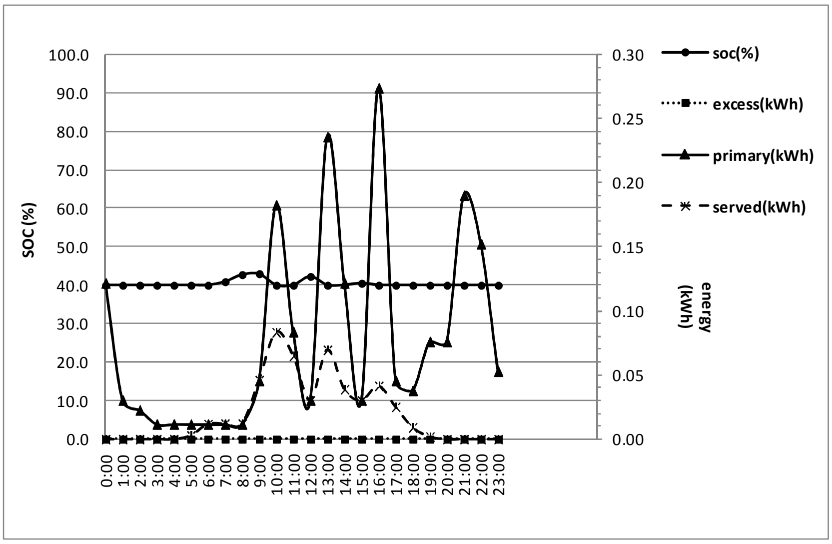


Figure 5.31 Typical house for a weekend day in June.

Almost the same response characterizes the system during the simulation of the typical house's load during the period of July-August, as Figure 5.32 and Figure 5.33 depict. The only difference between the two summer periods is SOC which almost reaches 60% in early afternoon of a typical weekday due to the environmental potential, but this later decreases when the demands increase and after one hour remains constant at 40%, thus indicating that the battery bank is totally empty and rendering the system out of order.

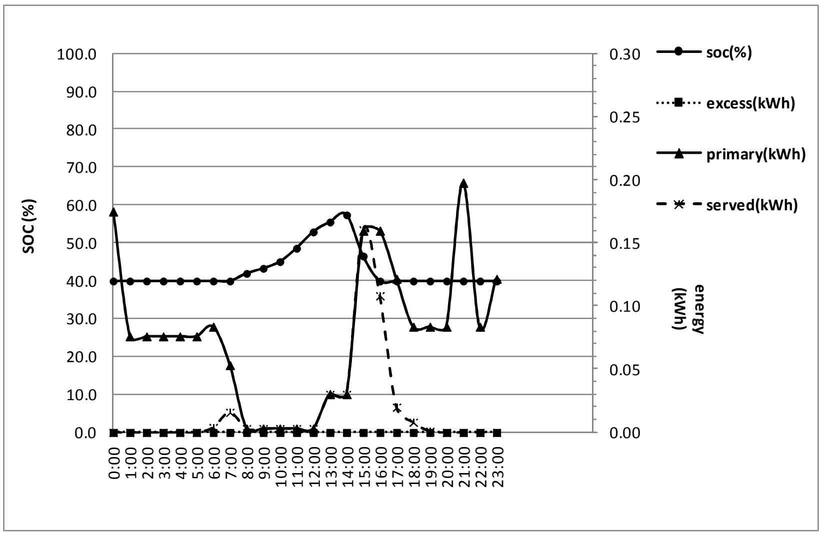


Figure 5.32 Typical house for a weekday in the July-August period.

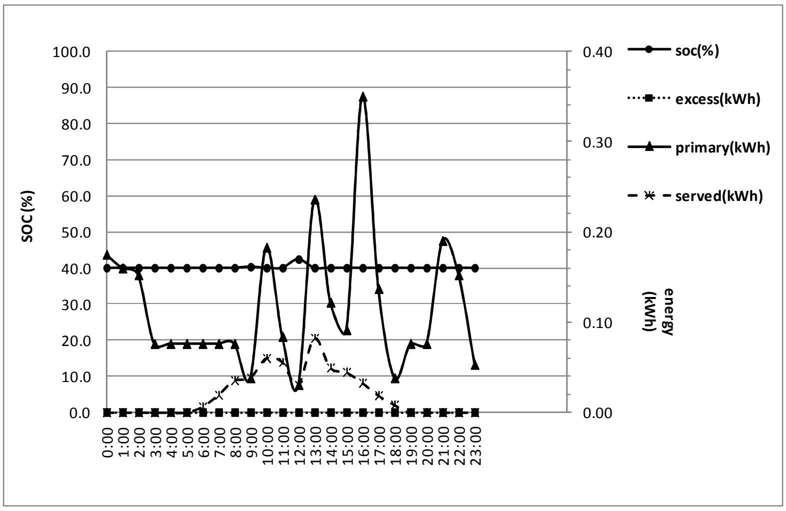


Figure 5.33 Typical house for a weekend day in the July-August period.

The same behavior is also observed for the typical country house. The desirable loads cannot be satisfied even during summer. Only for specifically low demands, such as those of a typical weekday in June when the country house is usually without residents, i.e. all loads are significantly low (Figure 5.34), is the system sufficient. Otherwise it fails totally, despite the excellent meteorological conditions prevailing in July-August (Figure 5.35).

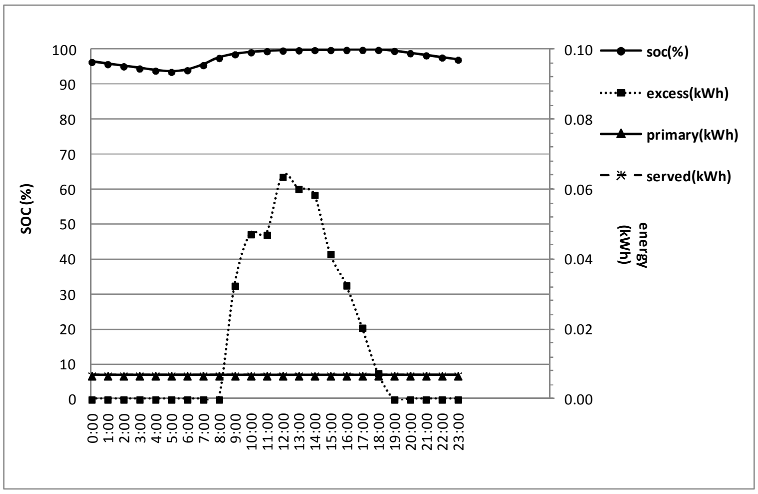


Figure 5.34 Typical country house for a weekday in June.

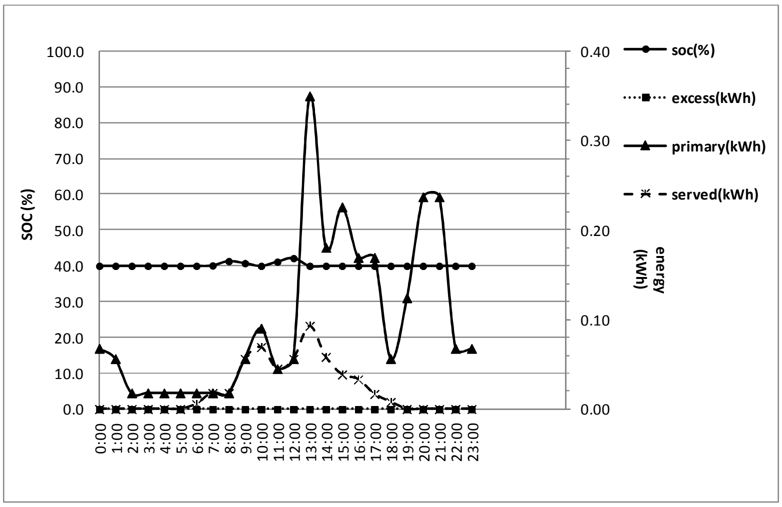


Figure 5.35 Typical country house for a weekday in the July-August period.

It is clear that the results achieved by the HOMER simulations are worse for the cases of winter, spring and autumn. Finally, the HOMER simulations show that the system fails to cover the demands of a typical small company for any season or day (weekday and weekend) with the exception of August weekends (Figure 5.36) when the load is very low (0.003 kWh) and the environmental potential is more than enough to satisfy it, while batteries remain almost fully charged at the end of the simulated day.

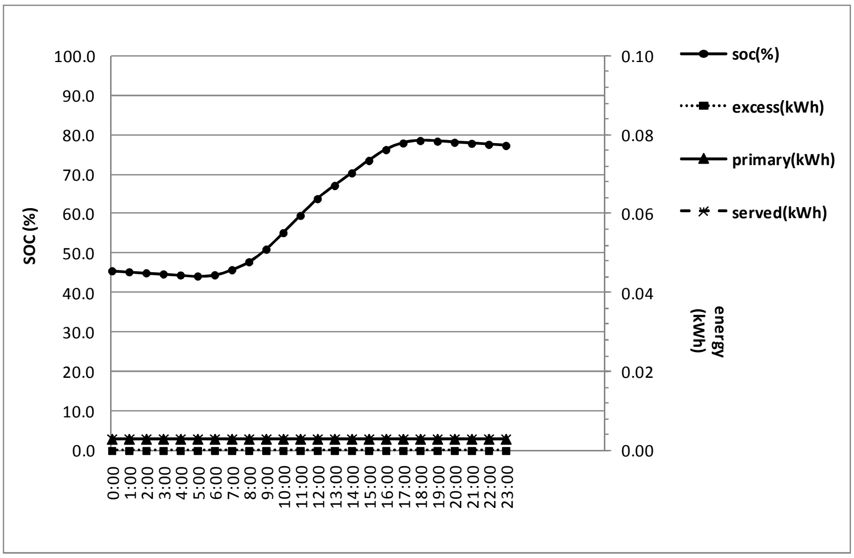


Figure 5.36 A typical company in a typical weekend during August.

Analysis of HOMER models and its main drawbacks - The simulation results are far from realistic and various operational parameters should be examined and determined from scratch. The HOMER software tool found that during spring and autumn the desirable load for a typical house can only be covered for 33% of the total hours of a single day. This result is similar to a typical weekday during the July-August period, but it falls to 25% in June, and nears zero in winter. The system therefore cannot cover the primary electricity requirements', meaning that the capacity of the RES based equipment is insufficient, thus corresponding to its significant over-sizing. In other words, HOMER indicates that electricity demands of a typical house cannot be covered totally even for a single day of one whole year. This is in contradiction with the real-time data series obtained from the established system as presented in the experimental part in Section 5.1, where the annual coverage is about 95%. The typical country house's simulation in HOMER shows that the primary load can be fully satisfied by the RES based stand-alone system for a common weekday from September to June. From July-August there is coverage of 25%, while the coverage of weekend demands varies from 62.5% in June, 50% during autumn, and close to zero during a typical weekend day in winter. The simulation results are similar for the coverage of the load of a typical house. During a whole year there is not a single day where the served load is capable of meeting the primary electricity demands apart from weekdays in August when the load is at its lowest.

From the above analysis arising from the theoretical simulation of the equipment for three small-scale projects, some serious misunderstandings arise compared to the analysis of the real-time data series of the experiments. In the majority of the simulations of the experimental process, SOC commences from 85% at the beginning of each day and the system operates steadily until the end of day using a large amount of stored energy. It is therefore clear that SOC is the most important parameter required to extract the correct operational results. In the real-life scenario, this parameter appears to fluctuate between 85% and 58% and is restricted only by the capacity of the inverter which cannot operate under 10.5V, even though the battery bank can offer sufficient energy to the system. In the HOMER simulation, the SOC value cannot exceed 60%, which means that the battery bank is almost at the end of its operational limit and cannot cover the primary load even in combination with RES based technologies. During the theoretical analysis using the HOMER package, the SOC cannot be accurately calculated at each time step. Therefore, the best currently available simulation tool cannot predict accurately the operation of the battery bank. Moreover, it is observed that the capacity of the battery bank under real-time operational conditions cannot meet the theoretical value exactly. Therefore, the electrochemical storage bank has a discharge efficiency of approx. 85% and can never meet the theoretical value of 100% as shown in Figure 5.34. Analysis of these results suggests that an extensive over-sizing is essential in order for the system to operate throughout the year under stable conditions. However, this is not realistic scenario, as the operation of the established system reveals. Thus, the design of a new simulation model is necessary. This model should be based on the accurate prediction of a battery bank's SOC to cover a specific load on an hourly basis during the simulation process. In general, SOC is described in analogy with the ratio of the energy input over battery output and can be predicted by measuring the operational voltage during a specific hour of the day, as discussed in the Experimental process of Section 5.1 in part (b).

Design and validation of a new software simulation model - The above theoretical analysis on the energetic feasibility of stand-alone RES based systems lead to the design of a new software simulation model that is based on an hourly scale load and daily scale environmental potential. One of the main differences of this new software compared to HOMER, is that the inputs for environmental conditions are the averaged values of a specific hour of a typical day during each season of the year instead of the average values of a whole month. In addition, by correlating SOC with the battery voltage, as presented previously, SOC values are calculated more accurately than in any other existing software simulation tool.

The innovative approach proposed here is based on fundamental physics that are widely accepted and have been already applied in several existing software simulation tools. The main differences focus on a daily simulation process and the mathematical description for the operation of the electrochemical battery bank, which uses complex energy balances. Following the circuit applied in the experimental system (where all the DC RES-devices supply their energy to the storage bank which in turn provides the required energy via the incorporated inverter as described in Section 5.1), the core of the simulation model is the battery bank. Power from RES-technologies can easily be calculated whenever the average hourly meteorological data are known. Therefore, the remaining capacity of the battery can be easily calculated by taking into account the coverage of the desirable load of the previous hour the storage bank was used to satisfy the demands. The innovative approach used in this model is based on the accurate prediction of battery SOC by using Equation 5.1.

Based on exactly the same environmental conditions and the same equipment, the simulation of the three different projects was performed using the new software and compared to the experimental process. For the case of a typical house, the primary load during a typical weekday in autumn is fully covered by the energy provided, and a small amount of excess energy is produced by the RES based technologies, while SOC is found to be over 40% at the end of the day (Figure 5.37). The same results were obtained for the same load in spring. For a typical weekday with low environmental potential during winter (Figure 5.38), the energy produced cannot meet the electricity requirements for the last three hours of the day.

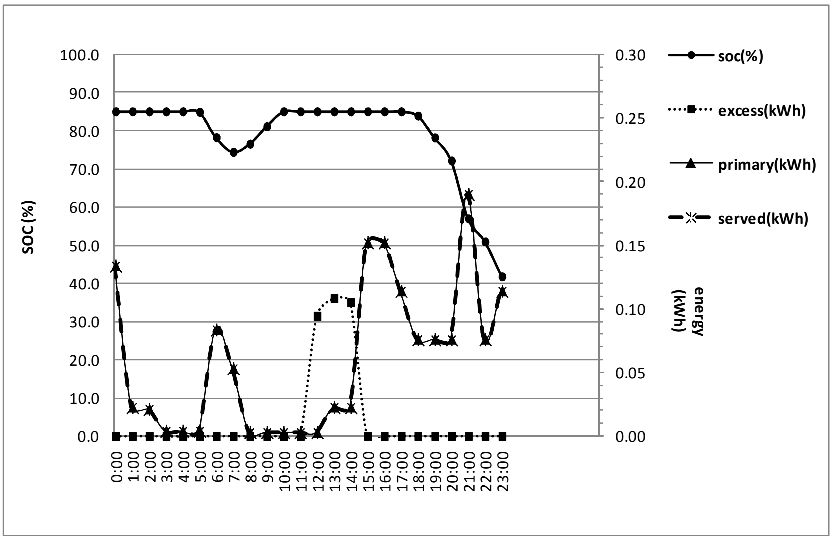


Figure 5.37 A typical house for a weekday in autumn.

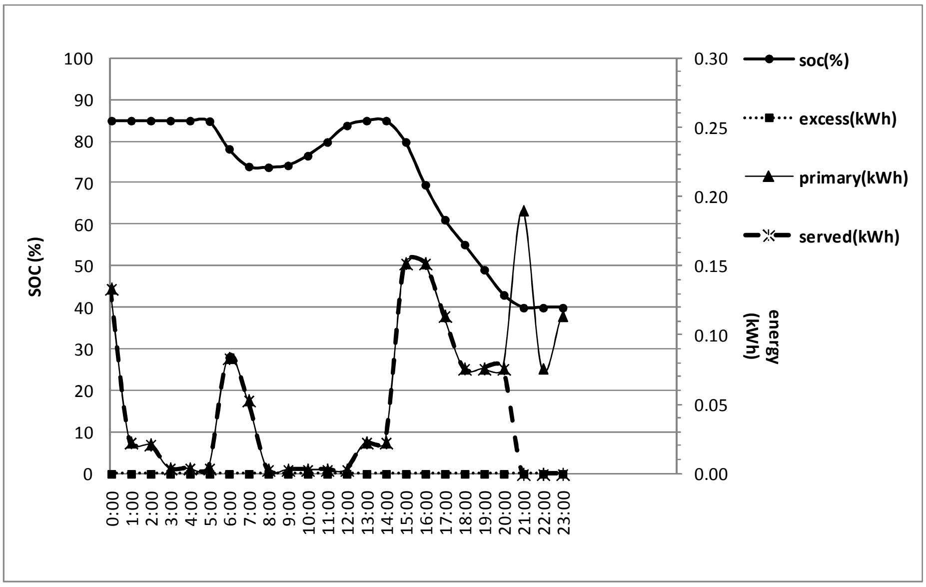


Figure 5.38 A typical house for a weekday in winter.

Figure 5.39 shows that the primary energy during June can be satisfied totally, although the SOC drops to 69% during early morning, later reaches 85% due to the high environmental potential, and finally drops to 45%. Similar results arise from the simulation of the July-August period, as presented in Figure 5.40.

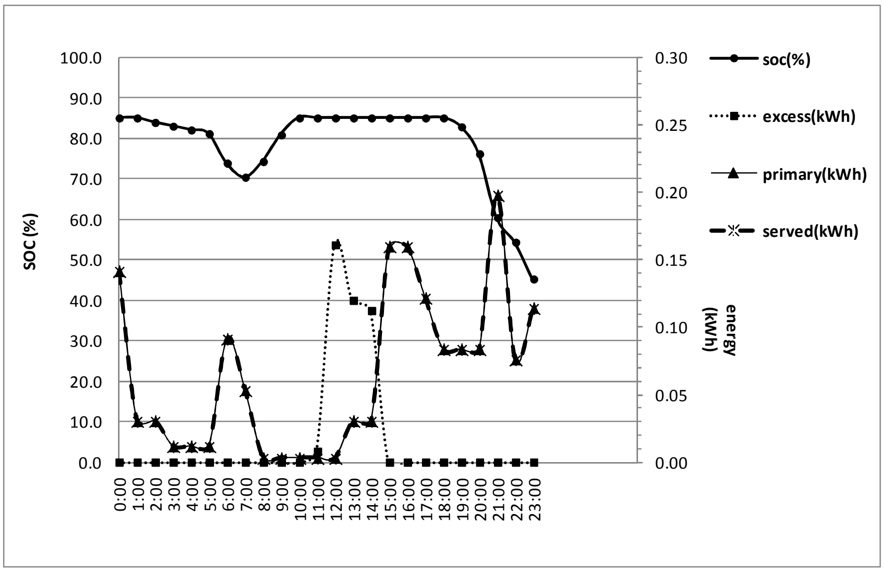


Figure 5.39 A typical house for a weekday in June.

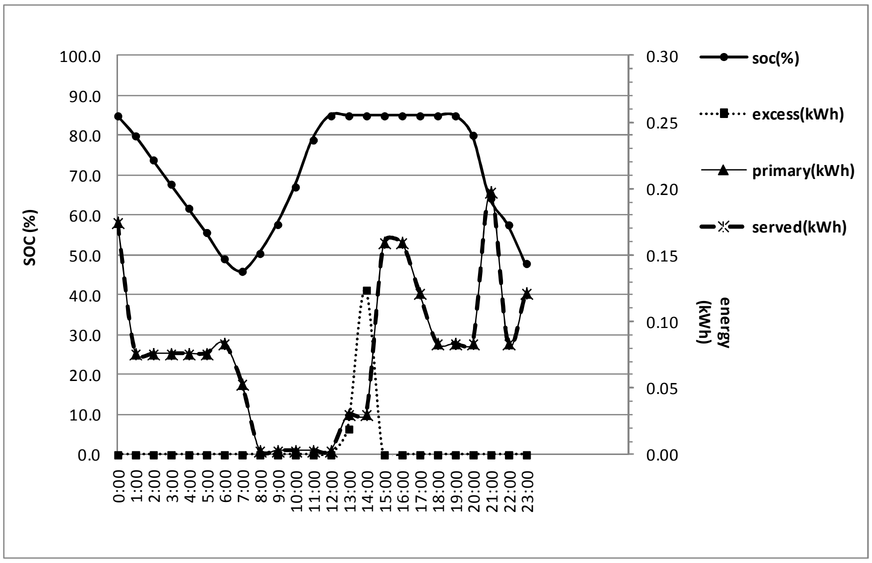


Figure 5.40 A typical house for a weekday in July-August.

During a typical weekend day in autumn, large fluctuations of the primary load are observed and these should be covered by the produced load. During autumn and spring, these electricity requirements can be satisfied all day except the last hour (Figure 5.41), while SOC of the storage bank reaches the limit under which the whole system shuts down.

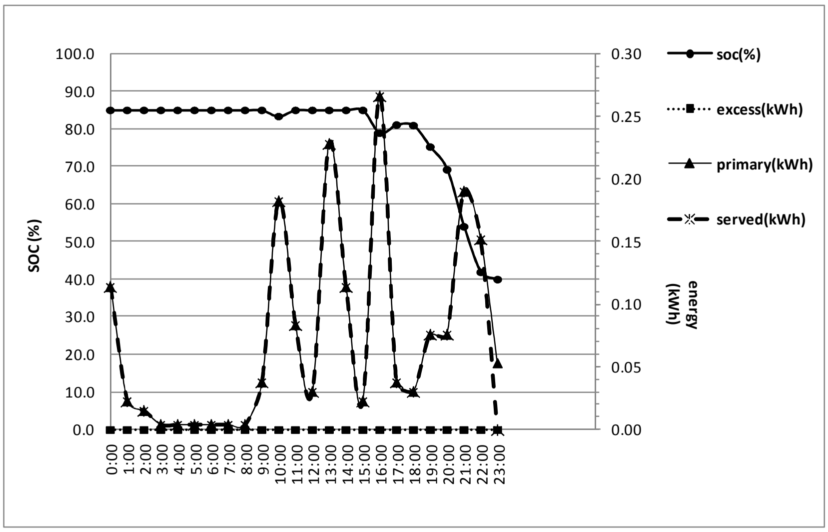


Figure 5.41 A typical house for a weekend day in autumn.

The simulation produced similar results for a weekend day in winter as Figure 5.42 presents, with the only difference being that the system shuts down in late afternoon and not just the last hour of the day, due to the low environmental potential characterizing the specific season.

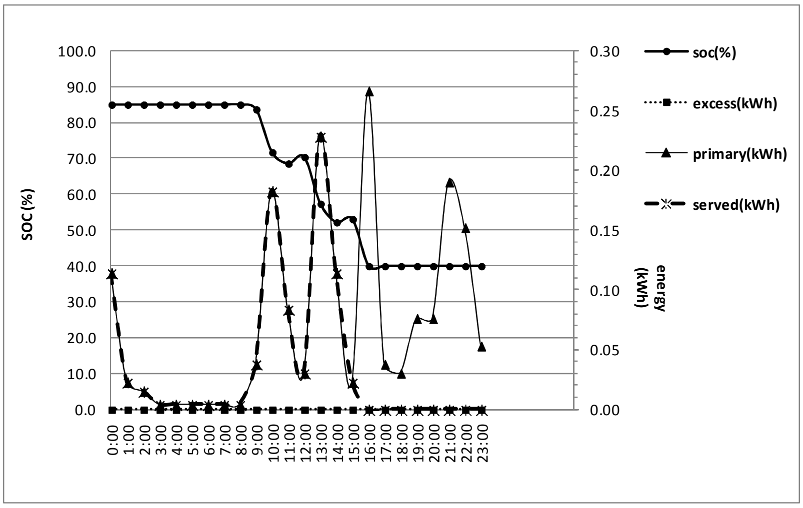


Figure 5.42 A typical house for a weekend day in winter.

In June, electricity demands are adequately covered by the system (Figure 5.43). However, in July-August this is not the case as the primary load increases and even if weather conditions are favorable, the system remains inactive from late morning to the end of the simulated day (Figure 5.44).

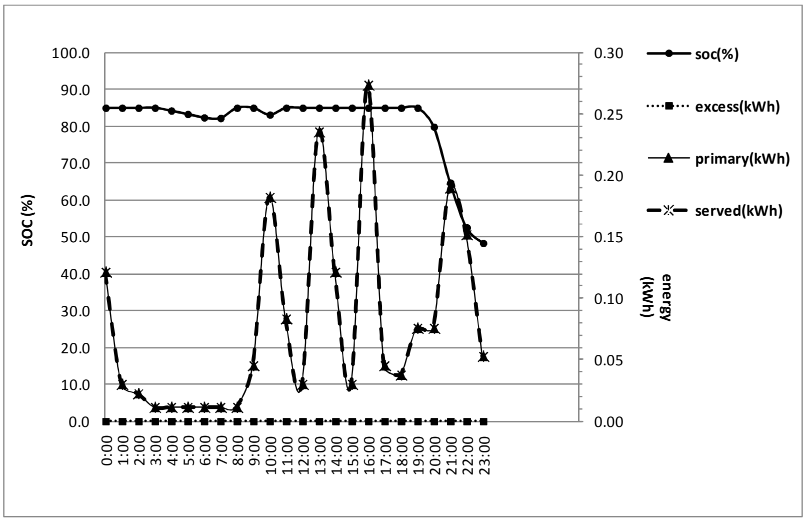


Figure 5.43 A typical house for a weekend day in June.

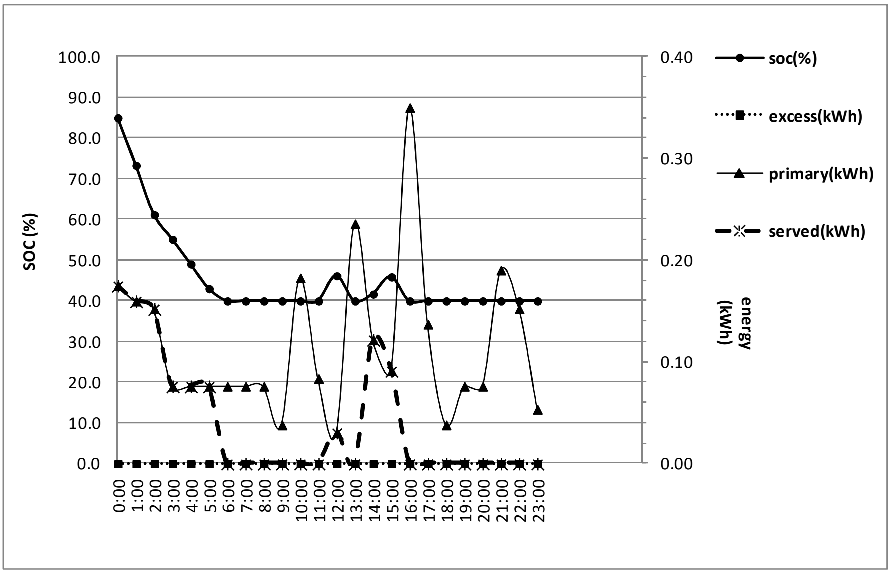


Figure 5.44 A typical house for a weekend day in July-August.

For the same period, the experimental process showed that the system shuts down from early afternoon to the end of the day, whereas the HOMER simulation indicated that the system cannot satisfy even a single hour of the day. This shows that the new simulation software tool is in better agreement with the experimental results than HOMER.

Regarding the coverage of a typical country house's load from September to June, the desirable load of a common weekday for this project is constant at 0.007kWh. Therefore, the most interesting results are expected from the simulation of a typical winter day due to its low environmental potential. In this case if the served load can meet the primary, then successful load coverage can be achieved in each scenario because of the more favorable weather conditions. Figure 5.45 presents the system's operation during a typical winter weekday when SOC remains at 85% throughout the day and the electricity demands can be covered totally by the RES based technologies. The same results were produced for the system's operation in autumn, spring and June with the only difference seen in the excess energy that fluctuates at higher levels due to the weather conditions.

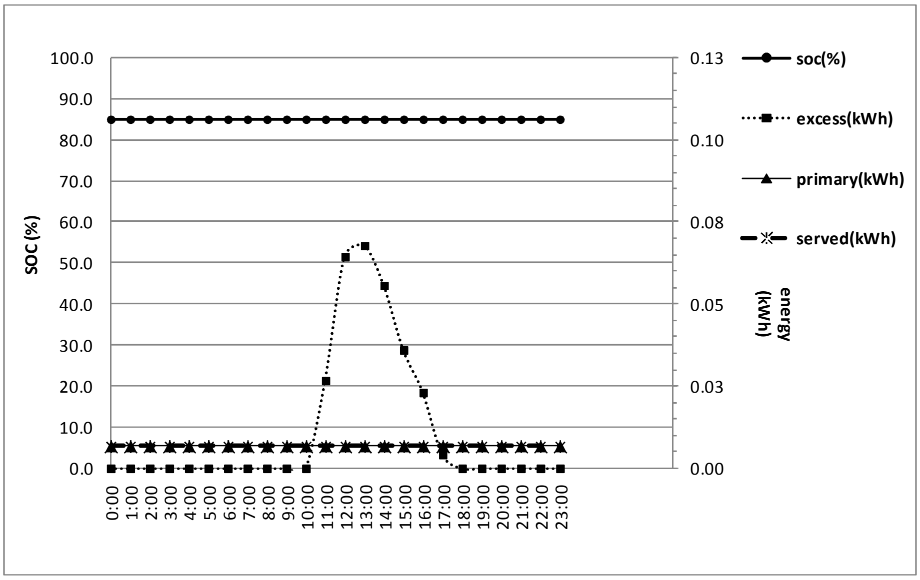


Figure 5.45 A typical country house for a weekday in winter.

A typical weekday in July-August is characterized by a different load with enormous fluctuations that cannot be fully covered, as Figure 5.46 reveals. The system is able to satisfy the desired loads until late afternoon when the SOC drops to 40% and the system stops serving the load and shuts down.

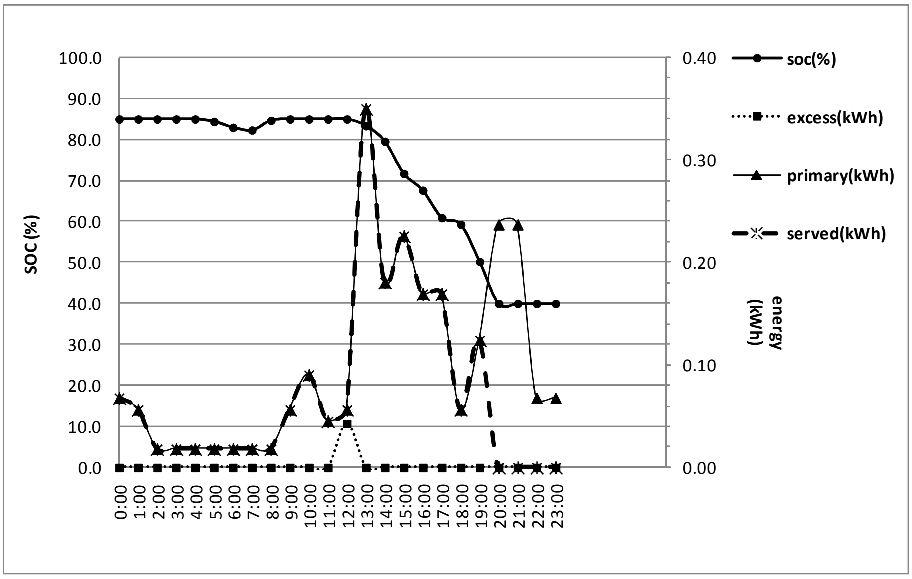


Figure 5.46 A typical country house for a weekday in July-August.

On the other hand, the operation of the system in real-life conditions, for a typical weekday during the same period, reveals that the system fails two hours earlier than the time indicated by the simulation. This occurs due to the operational restrictions of the inverter, which cannot operate under 10.5V while SOC must always be over 40% to protect the battery. By applying a higher power inverter, the discrepancy between experimental and simulated results would be significantly lower.

Concerning a typical weekend day from September to May, the simulation results show that the electricity demands can be satisfactorily met by the "green" energy provided except during the last two hours of the day (Figure 5.47). The same behavior characterizes the system during spring, while the coverage of this specific load during winter is poor and the system fails in late afternoon (Figure 5.48). The SOC bank sharply decreases during midday hours due to the served peak load, while the environmental potential is not high enough to cover the primary load and simultaneously charge the storage bank.

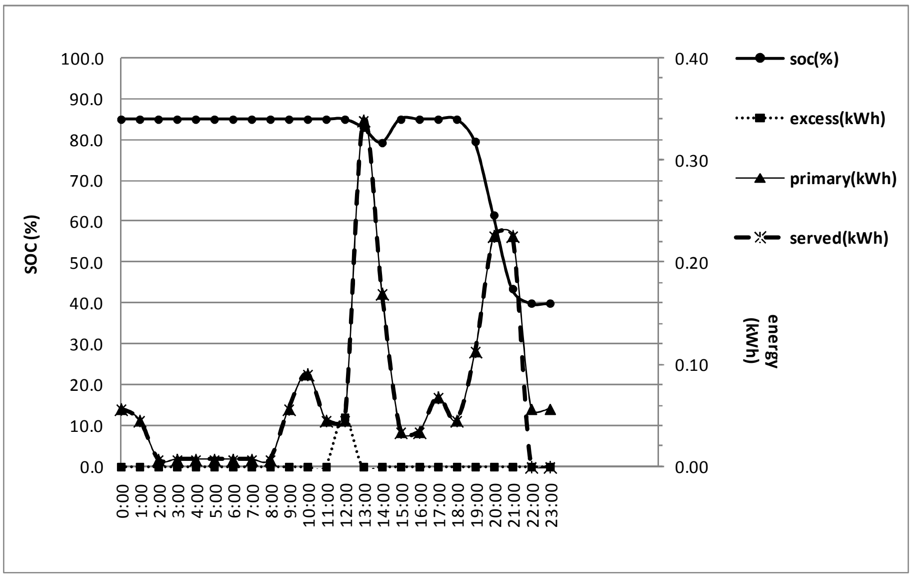


Figure 5.47 A typical country house for a weekend day in autumn.

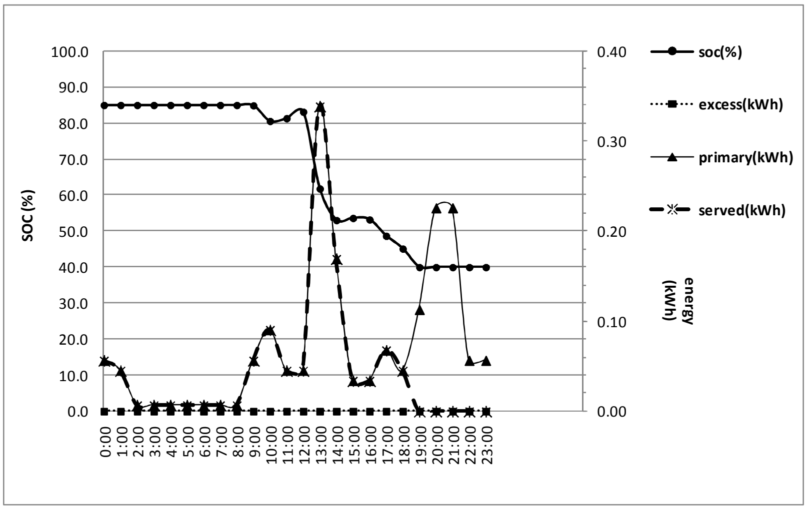


Figure 5.48 A typical country house for a weekend day in winter.

The local environmental potential is a crucial factor when deciding to establish an RES based system. Figure 5.49 presents an identical load for a typical weekend day in June, when the primary load is almost fully covered apart from the last hour of the day, thus indicating that the capacity of the system is sufficient enough for the stable operation of a typical country house in this period. Finally, for the country house, a typical July-August weekend is characterized by the same electricity demands as a weekday during the same period, thus the results are identical to those shown in Figure 5.46.

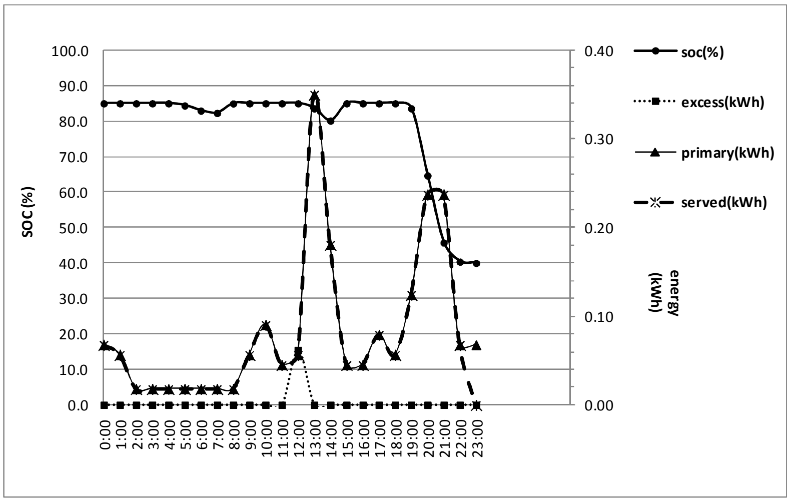


Figure 5.49 A typical country house for a weekend day in June.

Next, the load of a small company was considered. During a typical winter weekday, the load can be covered totally by the established technologies and the SOC does not drop below 68%, which means that it retains a substantial amount of stored energy (Figure 5.50).

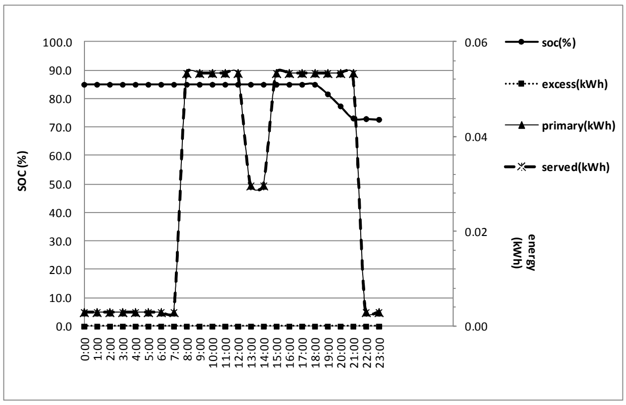


Figure 5.50 A typical company for a winter weekday.

The same load must be covered during both autumn and spring and this is found to be feasible because during these periods the environmental potential is higher than in winter. The only notable difference is that throughout the above periods SOC remains constant at 85% at the end of the day, therefore the storage bank is fully charged and there is a significant amount of waste excess energy.

The simulation of a typical small company's load during a typical weekday in June-July is depicted in Figure 5.51.

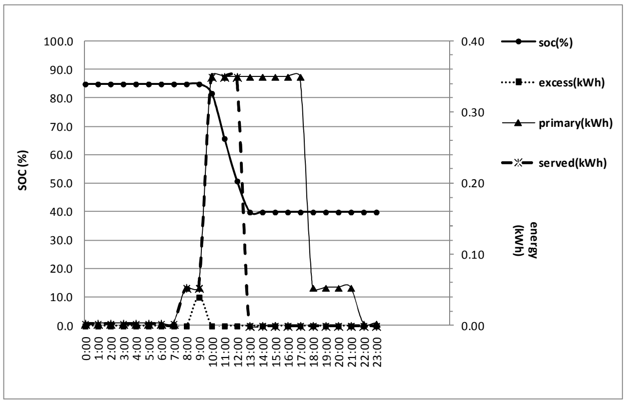


Figure 5.51 A typical company for a weekday in the period of June-July.

Here, the served load is not sufficient to cover requirements and the battery bank is fully discharged from early afternoon to the end of the day. This occurs because the peak load remains high for a long period at midday. Exactly the same behavior characterizes the operation of the system in August where the load is similar.

For a typical weekend day in September to May, the results are identical to those of a winter weekday (Figure 5.50) because the desirable load is slightly lower than that of weekdays and can be fully covered by the served energy, while the battery bank remains fully charged. The results for summer weekends in June-July are identical to those depicted in Figure 5.51 because the relative loads are also identical. The electricity requirements of the small company during a typical weekend day in August are constantly very low (0.003kWh) and thus fully satisfied by the “green” energy without contribution from the battery bank. Thus, high amounts of excess energy are wasted as Figure 5.52 presents.

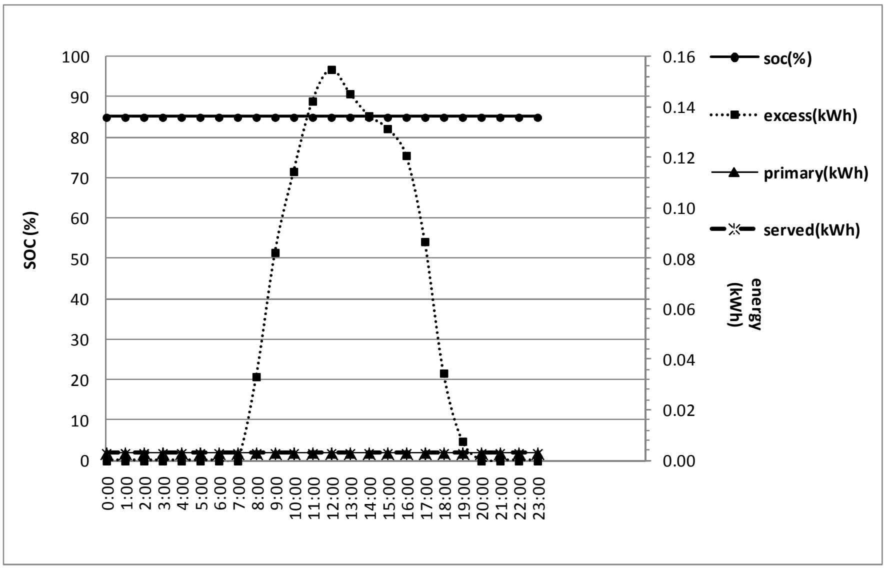


Figure 5.52 A typical company for a weekend day in August.

General conclusion - The theoretical analysis of simulations using a new software simulation tool revealed that an RES based hybrid system can fully cover the load of a typical house in weekdays of one year except during winter when coverage reaches 87.5% of the hours of one day. The simulation showed that the capacity of the established equipment can adequately cover the needs of a whole day based on real-time data, in contradiction to results arising from simulations using HOMER software. For the weekends, the behavior of the system changes because the coverage of the load reaches 75% in winter and drops to 20.8% in the July-August period. However, it can be concluded that the model represents the real-time operation of a RES stand alone project more accurately than the HOMER platform because the total coverage of the desired electricity demands reaches 89% for one whole year in the case of the typical house. This improved accuracy is ensured as the new simulation tool is strictly designed on an hourly data basis and the SOC of the electrochemical battery bank.

Simulations on the operation of the hybrid system to cover the electricity requirements of a typical country house show that the load served from “green” technologies can satisfy the primary load of a typical weekday from September to June. During periods characterized by a high peak load, such as July and August, the coverage reaches 83.3% of the hours of one day. By analyzing the final results of simulated weekends throughout one year, the energy produced by the hybrid system can adequately satisfy the desirable load of a typical country house with a percentage that fluctuates from 96% to 75% on a typical winter weekend day. Almost the same situation is seen in real-life scenarios.

Regarding simulation of a typical small company’s load, from September to May the electricity requirements of a typical weekday and weekend can be fully satisfied by the RES based equipment with a substantial amount of energy remaining in the storage bank. In contrast, for the June-July period with increased needs, only 50% of the total hours can be covered. The total number of days that can be satisfied by the system during a whole year is approx. 77%, which strongly agrees with the real-life scenario. The new tool simulates real-life scenarios more accurately than the HOMER simulation tool, and can therefore assist the planning and design of small-scale projects.

To summarize Chapter 5, three different RES based hybrid systems characterized by different loads were simulated on a yearly basis using the HOMER software platform to verify real-time results arising from the experimental process.

The hybrid systems are based on photovoltaic and wind energy in combination with an electrochemical storage bank to cover small-scale desirable loads of a typical house, a typical country house, and a small company. Analysis reveals that HOMER software cannot successfully simulate the operation of the battery bank.

The State of Charge of the electrochemical storage bank is about 40% in the majority of examined cases, thus indicating that the battery plays an insignificant role in load coverage. Served load cannot meet the primary load and the whole system fails for long periods during the year. To overcome this situation with HOMER, a substantial over-sizing on the capacity of established technologies is necessary while the real-time data reveal the opposite.

Finally, a new approach based on the accurate management of the storage bank using a specific mathematical model was designed and applied. The new approach was found to produce simulations in excellent agreement with experimental results.

The next chapter will reveal the necessity of buffering systems in RES based hybrid systems and how they can be more eco-friendly by incorporating innovative approaches into the already simulated systems.

Box 5 Summary of the new software simulation tool.

6 INNOVATIVE BUFFERING TECHNOLOGIES

Renewable Energy Sources are characterized by their unpredictable behavior, since their availability depends on local meteorological conditions. Therefore, the use of intermediate energy storage (buffering) is essential for an uninterrupted energy supply, especially for off-grid stand-alone systems.

6.1 OTHER STORAGE TECHNOLOGIES EXCEPT ELECTROCHEMICAL BATTERIES

6.1.1 THE WEAKNESS OF SEVERAL TECHNOLOGIES AND A NEW PROPOSAL

Buffering systems are categorized according to the energy they supply and their initial cost. Besides the well-known electrochemical batteries there are numerous buffering technologies such as hydrogen technologies via electrolysis, super capacitors, and compressed air pumps that are used in mobile or medium-scale applications (Wang et al., 2013). It has been also presented that the most conventional and commercialized way to overcome the buffering problem is by using electrochemical batteries that take advantage of new hi-tech materials which extend their lifetime, minimize their size, and increase their power outputs.

Although batteries technologies have evolved considerably they still present specific drawbacks: their pollutant character at the end of their lifetime, their lifetime is very short compared to the whole project's lifetime (a typical battery operates for 5 to 7 years while the lifetime of a typical stand-alone RES based power plant is about 25 years) (Peter and Euan 2008). The lifetime of electrochemical batteries can be extended by ensuring fully completed charge/discharge cycles. However, this cannot be strictly followed because both the weather conditions and the electrical demands of a system are unpredictable.

Another immature but promising energy buffering method is the production of hydrogen through electrolysis by supplying RES-produced electricity and its consumption in a fuel cell (Clarke et al., 2010). This process is very stable with a totally eco-friendly character, especially if the desired electric energy used by the electrolysis process comes from "green" sources such as photovoltaic panels or wind turbines. However, there are numerous drawbacks with this option, including the extremely high costs (because of several safety issues) required for its installation. Moreover, low efficiency is another factor limiting the wide use of H_2 in RES based projects. Multiple transformations of energy occur throughout the process in three phases: hydrogen (fuel) production, hydrogen storage, and production of electricity by the fuel cell. Additionally, the installation of a hydrogen-fed system requires large surface areas which are not available in the majority of small investments (Shabani & Andrews, 2011, Ulleberg et al. 2010). However, this technology can be incorporated into an RES system efficiently if the system is accurately optimized.

Super capacitors have also been tested as electrochemical battery substitutes. Although they present several advantages compared to typical batteries, such as unlimited life time, no full charge circuit required and quick charging times, they cannot be used widely due to serious disadvantages. These are the low energy density, high self-discharge, and the low voltage cells. The existence of low voltage cells requires their serial connection to obtain higher voltages, and when more than three are serially connected the circuit requires a voltage balancing element (Abruña et al. 2008).

A state-of-the-art eco-friendly device, which can be charged and discharged several times with high efficiency and that demonstrates stable performance during a project's lifetime, in combination with low investment costs, is essential for the total commercialization of the buffering technologies based on RESs. To this end, flywheels appear to be a feasible solution since they demonstrate numerous advantages compared to more conventional technologies such as electrochemical batteries and hydrogen-based equipment.

6.1.2 ADVANTAGES AND DISADVANTAGES OF FLYWHEELS

Flywheels have long lifetimes and this is one of their main advantages because they can be charged and discharged at high rates for many cycles without efficiency losses. These losses approach values of 80 to 90%, as shown in Figure 6.1 where the average efficiency of each buffering technology is presented against an average operational time, estimated rather qualitatively (Bleijs et al. 2000, Ledjeff 1990, Liu and Jiang 2007).

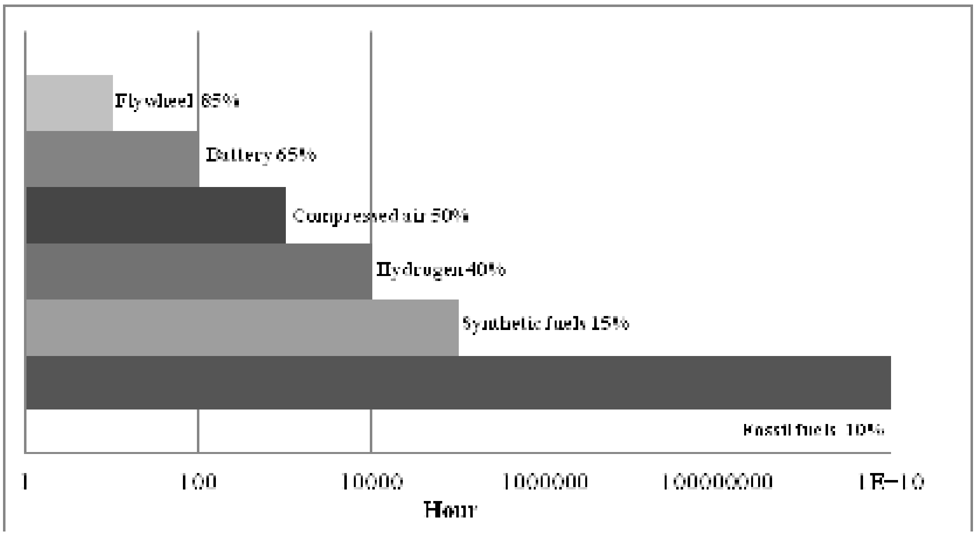


Figure 6.1 Comparison of different technologies in terms of efficiency as a function of time (Ledjeff, 1990).

A Flywheel Energy Storage System (FESS) can also be connected to either an AC-bus, offering a huge variety of frequencies, or a DC-bus depending on the demands of the hybrid system for the coverage of the desirable load (Bolund et al., 2007). Flywheels could be an integrated green technology because their operation is not supported by chemicals and also their raw materials are totally recyclable (Liu and Jiang, 2007).

The main disadvantage of flywheels is their limited storage time. For the majority of commercialized flywheels this is attributed to high standing losses since a remarkable percentage of their stored capacity is wasted through the marvel of self-discharge. These rates are found to be in the range of 0.18 to 2.0 times stored capacity per hour (Farret and Simoes, 2006). This phenomenon can be diminished by the use of state-of-the-art materials such as carbon fibers or by the combined use of more conventional technologies. However, this would increase dramatically the cost of such an installation thus the combination of different technologies seems to be a realistic selection for everyday life RES based systems.

This chapter presents several RES based hybrid systems that contain flywheels in combination with other more mature technologies for energy buffering in order to prove their feasibility and demonstrate how they can improve the behavior of autonomous systems. The process of their incorporation will be finalized through simulations. The current trends on designing a FESS will be presented by implementing one into an autonomous RES based system under real-life conditions. Finally, FESS will be compared with other mature and commercialized technologies that have been used in small scale applications.

6.1.3 BASIC THEORY ON FLYWHEELS: PHYSICS & ECONOMICS

Nowadays flywheels seem to have a new look based on an old idea, since they are used as electromechanical batteries (EMB) for intermediate energy storage (Niiyama et al., 2008). Flywheel-based energy storage systems are modular devices containing a flywheel stabilized by nearly frictionless magnetic bearings, integrated with a generator motor and housed in a sealed vacuum enclosure (see Figure 6.2).

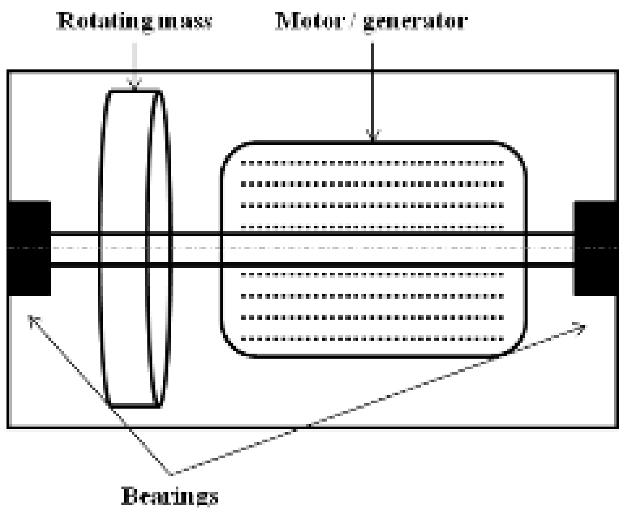


Figure 6.2 Design of a typical FESS.

The EMB is charged by spinning its rotor mass to maximum speed either by an electric or a non-electric motor that takes advantage of excess energy that could be produced by RES. The EMB is then discharged by slowing the rotor of the same motor at reverse mode to convert the stored kinetic to electric energy (Bleijs et al. 2000, Liu & Jiang 2007).

The design of such a device (especially the rotating mass) and the materials used for the construction of a flywheel are crucial. It is essential to use hi-tech materials such as high-strength fiber composites, especially graphite as the flywheel's energy storage capacity depends on these fibers because a spinning rotor has an upper speed limit determined by the tensile strength of the material (Bleijs et al. 2000, Liu & Jiang 2007). For a given rotation speed, the amount of kinetic energy produced is determined by the rotating mass. Furthermore, the design characteristics have to take into account both the operational parameters and the investment and maintenance costs.

The calculation of general characteristics and the operation of a flywheel can be described by fundamental physics. The stored energy in a flywheel can be calculated by Equation 6.1 (Bleijs et al., 2000).

$$E = \frac{1}{2} I \omega^2 ,$$

where ω is the rotational speed and I is the inertia of the rotor.

Equation 6.1 Kinetic energy stored in a flywheel.

The inertia of the rotor mass is presented in Equation 6.2 and is influenced by the shape and material of the spinning mass.

$$I = \int \rho(x) r^2 dx ,$$

where $\rho(x)$ is the density of the rotational mass and r is the radius.

Equation 6.2 The inertia of the rotor mass.

It is also necessary to calculate the maximum kinetic energy per unit mass, which follows the limitations of the construction's material. This is given by the following expression (Bolund et al., 2007):

$$E_m = K \frac{\sigma}{\rho_{met.}} ,$$

where K is the shape factor, depending on the shape of the rotor mass, σ is maximum stress of the flywheel's metal construction, and $\rho_{met.}$ is density of the construction material.

Equation 6.3 The inertia of the rotor mass.

Following the energy analysis, a financial analysis is considered as essential to reveal the feasibility of FES systems and under which conditions they could be incorporated into RES based system. The financial analysis is based mainly on the NPC (Net Present cost) of the FES system as presented in Chapter 2.

6.2 Simulations of Economic and Technical Feasibility of Battery And Flywheel Hybrid Energy Storage Systems in Autonomous Projects

Background - Autonomous systems are based on different storage technologies and have been simulated in various locations around the world. The basic aim is to obtain useful results by comparing conventional storage technologies (electrochemical batteries) with less mature ones (flywheels and hydrogen).

Originally, attempts were made to use flywheels as the unique energy storage systems in some space power applications where solar is the primary source of energy. The lack of gravity combined with their huge operational storage densities, compared to more conventional technologies, provided ideal conditions for their use (Olszewski, 1988). They also replaced first generation space batteries and the nickel-hydrogen batteries used in spacecrafts to improve efficiency and reduce spacecraft weight and cost (Liu and Jiang, 2007).

Flywheels were later commercialized in the transportation sector and several mobile applications. Several studies on city buses were undertaken in order to take advantage of the kinetic power produced, save fuel and reduce greenhouse gas emissions (Tripathy, 1992, 1994). These projects used power supplied by ICE together with FESS or, in some cases, only by either the ICE or the FES system (Tripathy, 1992, 1994). The main idea of this concept was to accelerate the vehicle by using electrical energy generated by an FESS, because higher fuel consumption is recorded at the point of a vehicle's acceleration after a short stop in city traffic. The electric transmission of the hybrid vehicle requires two motors; one to set the vehicle in motion and the other to charge the FESS (Tripathy, 1992, 1994). During deceleration, the jackshaft of the vehicle acts as a prime mover which converts the kinetic energy to electrical through the traction motor-generator, and this, in turn, is converted to mechanical energy and stored in the FESS. For the second mode of operation, the FESS acts as a prime mover by generating electrical power which is fed into the traction system that accelerates the vehicle (Tripathy, 1992, 1994).

Nowadays the evolution of such a system is the Kinetic Energy Recovery System (KERS) which is used in Formula One race cars and is schematically shown in Figure 6.3.

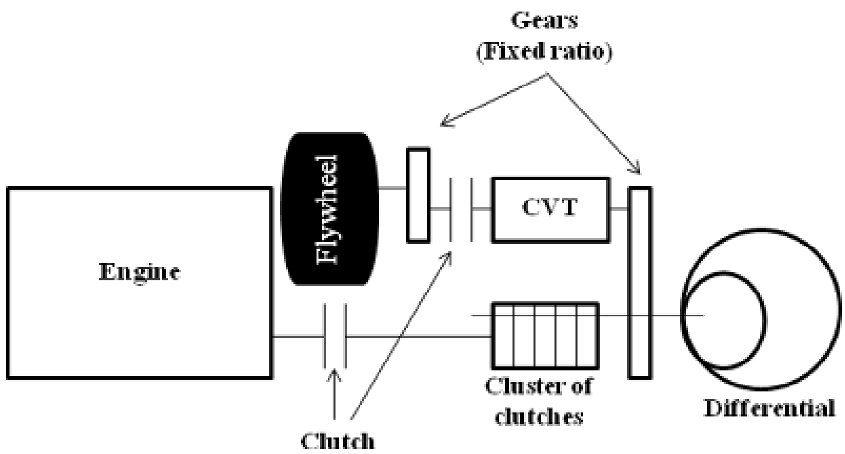


Figure 6.3 The Kinetic Energy Recovery System (Tripathy, 1992, 1994).

The KERS uses a flywheel for energy storage and a Continuous Variable Transmission (CVT) gearbox to transfer energy to and from the driveline. The CVT gearbox is essential because ratios of vehicle and flywheel speed are different during braking or acceleration (Boretti, 2010). More precisely, the revolutions per minute (rpm) under which the engine operates, reduce during deceleration to stabilize the rotation of the flywheel to a standard range. This system is the state-of-the-art on FESS which is used in mobile applications. Explicitly, the two clutches are necessary to distinguish the operation of the motor from the flywheel because these two systems have to rotate under different angular velocities. Also, the fixed ratio gears pass the motion to the CVT and the flywheel whenever necessary. Finally, the cluster of clutches is practically a CVT gearbox which is used to put the vehicle in motion.

Concerning stationary applications for energy storage, flywheel systems are at an early stage of development, because of the current trend in designing power plants. Nowadays it is common practice to oversize the whole establishment to ensure the full coverage of electricity demands. The opposite is true for mobile applications where the size and weight of the power unit have to be low. Therefore, the rotor mass is large and heavy in stationary applications and any excess electricity from RESs is not enough to charge such a system. Some research is being conducted on stationary applications and mainly focuses on the use of FESS as auxiliary devices to control high fluctuations of electricity during the day such as UPS (Brown and Chvala 2005, Suzuki et al. 2005).

One techno-economic analysis of different storage systems used in RES based autonomous electrical networks identified the benefits of using flywheels in small-scale RES based projects. Specifically, this study was undertaken in the Aegean Islands where the electricity balance status is currently determined by the operation of oil-based thermal power stations. More precisely, the existing electricity networks were classified into four main groups based on their annual energy consumption and the corresponding peak load demand. The first one comprised eight small islands, the second group comprised seven relatively small islands, the third includes thirteen medium-sized islands, and the fourth comprised all the large Aegean islands (Kaldellis et al., 2009). The electricity demands of all the networks were planned to be covered by a hybrid system based on wind and solar potential and was simulated with different energy storage options for each group. Especially notable are the results arising from the simulation of the first group of islands with an average annual electricity consumption of 900 MWh and a corresponding peak load demand of 300 kW. The many advantages of using flywheel systems as backup energy storage units were highlighted in this study (Kaldellis et al., 2009).

Another research study revealed a flywheel energy storage system that can supply up to 10kW in a wide range of spinning velocities for stable operation for an acceptable time period and than can be incorporated into small-scale hybrid projects as a backup energy system (Ichihara et al., 2005). This project was constructed to operate in real-life conditions but it remained in the laboratory and was not promoted for commercial use. The project focused on several major alterations to the flywheel system that would reduce friction losses but still provide enough electricity to cover the demands of a small system. A laboratory-scale flywheel with superconducting magnetic bearings was accelerated up to 7500 rpm with rotation losses equal to 40 W at these spinning velocities and a total running time of c. 6.5 hours. The resulting supplied energy was equivalent to 2.24kWh (Ichihara et al., 2005).

All the above studies on simulated and laboratory-scale projects for the coverage of specific loads revealed some key features on the nature of flywheels including: the high power and energy density, relatively low maintenance requirements, their environmentally-friendly character, their short recharging time, deep discharges, and their high overall efficiency value (≈85%) (Kaldellis et al., 2009). The main drawback of the above projects is that flywheel applications are not suitable for power rated higher than several hundreds of kW per day because their operational period is only in the order of a few hours. Some research has also been conducted on the implementation of FESS in off-grid applications, but the combination of FESS with batteries and/or ICE has not yet been studied (Arghandeh et al. 2012, Brown and Chvala 2005, Suzuki et al. 2005).

In this study, effort has been made for advanced technologies (such as flywheels) to be integrated into everyday systems, to aid their further commercialization. The simulation presented here was based on a specific load for a typical house located on Naxos Island. Naxos was chosen as the installation location due to its high RESs' potential as presented analytically in Section 3.2. All the systems considered were assumed to simultaneously utilize solar and wind energy and use a stack of batteries in combination with flywheels for energy storage.

Simulation process - Naxos Island was chosen for the typical case-study location, while the most efficient RES based hybrid stand-alone system, presented in Section 3.2 of this thesis, was simulated. Moreover, an extensive study on the selection of electrochemical batteries took place during the system design stage. The present simulation process is organized as follows:

the first step was the construction of a hybrid photovoltaic-wind system capable of covering the load of a typical house for one year. The second step was the choice of three different types of electrochemical batteries of different categories as a backup system for the energy produced in the system (powerful Hoppecke 3000 Ah batteries, deep cycle discharge Surrette 1900 Ah batteries, and low power Vision 55 Ah batteries). The same batteries were used for the simulations of the innovative storage system incorporating the flywheels. Finally, by including flywheels to store energy in the hybrid system a new system was constructed. This system is equivalent to a battery-type storage unit, combining a flywheel, a DC-DC converter and a battery. More precisely, the flywheel is permanently connected to a DC-DC converter for voltage regulation purposes between the devices (this is necessary due to the chosen DC current and parallel connection) as shown in Figure 6.4.

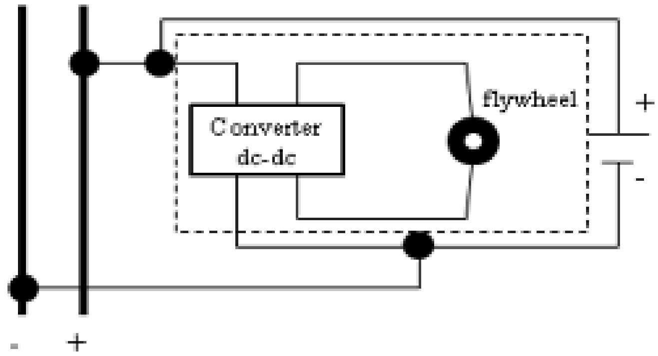


Figure 6.4 The innovative storage system.

The parallel connection of a flywheel and an electrochemical battery is an innovative approach for energy storage systems, therefore the results of these simulations are compared with those of conventional batteries to investigate if such a system is feasible in terms of energy and economy. A 10 kW high voltage flywheel was used in these scenarios and the main characteristics arising from the advanced combination of the components, are the round trip efficiency and the maximum charge rate (A/Ah) that is higher than the most powerful commercial battery (Perrin et al., 2006). The values used in the simulations are presented in Table 6.1. Specifically, the hybrid battery banks Flywheel + Hoppecke and Flywheel + Surrette operate under the very low nominal voltages of 2 V and 4 V, respectively. These characteristics are provided by the manufacturer and for this reason the use of a DC-DC converter was considered essential to adjust the specifications of the current driven to the hybrid battery bank in order to balance the whole system.

Operational characteristics	Flywheel + Hoppecke	Flywheel + Surrette	Flywheel + Vision
Round trip efficiency (%)	75.2	75.2	75.2
Nominal capacity (Ah)	4250	2525	263.33
Nominal voltage (V)	2	4	12
Minimum state of charge (%)	30	40	40
Float life (years)	30	30	30
Max. charge rate (A/Ah)	3.926	3.856	3.606
Max. charge current (A)	610	67.5	16.5
Lifetime (in cycles)	150,000	150,000	150,000

Table 6.1 Operational characteristics of the new storage devices.

Regarding the economic issues of this innovative product, attention should be given to the lifetime of each component because it differs between flywheel, converter and battery. Therefore the economic study was finalized without using the HOMER software tool which was used for the energetic optimization of the system. Costs were calculated separately for each component and were added to the project's final budget. The lifetime of each battery, converter and flywheel were chosen to be 10, 15 and 30 years, respectively. Moreover, the nominal interest rate and annual inflation rate were chosen to equal those of the Euro zone, i.e. 4% and 1.6%, respectively. During the simulations, flywheels of two different initial costs were used: 200 $/kW and 350 $/kW, equivalent to low and medium cost (Ruddell 1998-2002, Post 1996).

Results and General discussion - All the possible scenarios of the different combinations of storage systems were designed and implemented using HOMER software. The energy part of this optimization procedure was performed using HOMER but the economic study was finalized by hand using the mathematical model in the Simulation process of the present Section. The main drawback that arose from using HOMER, was that the specific simulation software tool incorporated flywheels in the form of load to be covered, rather than an energy storage device.

For this reason, the construction of the new storage system was considered essential for the incorporation of flywheels into a hybrid stand-alone system.

The scenarios designed and simulated are presented in Table 6.2.

Systems	Desirable load (kWh)	PV (kW)	Wind (kW)	Batteries	New batteries
PV, Wind and Hoppecke batteries	7775	1	1×5	4 (Hoppecke 3000 Ah)	-
PV, Wind and Surrette batteries		1	1×5	6 (Surrette 1900 Ah)	-
PV, Wind and Vision batteries		1	1×5	58 (Vision 55 Ah)	-
PV, Wind with flywheel and Hoppecke batteries		1	1×5	-	2 (Hoppecke 3000 Ah)
PV, Wind with flywheel and Surrette batteries		1	1×5	-	5 (Surrette 1900 Ah)
PV, Wind with flywheel and Vision batteries		1	1×5	-	10 (Vision 55 Ah)

Table 6.2 Scenarios for RES-based power plants.

Through system optimization it can be seen that each scenario was capable of covering the desirable load of a typical house (=7775 kWh/year). The desired (primary) load and unmet load produced by the stand-alone RES based systems are presented in Figure 6.5. It can be seen from this figure that the unmet load fluctuates at low levels.

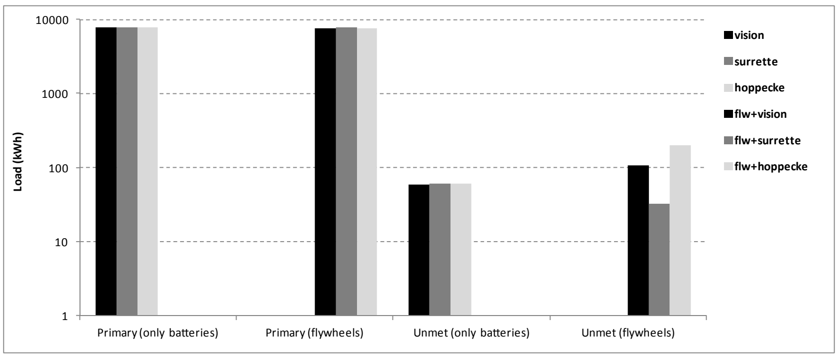


Figure 6.5 Produced and unmet loads of each system.

Figure 6.5 shows that the lowest unmet load is observed in systems with flywheels combined with Surrette batteries, and the highest is observed in systems combining flywheels and Hoppecke batteries. Although Hoppecke batteries are the most powerful, the economic optimization forces the system to operate without an extra new battery because the cost will increase greatly and, at the same time, the gain in energy will be limited.

The optimization of a system is always related to economic issues. A stand-alone RES based system using FESS for energy backup can be profitable, as depicted in Figure 6.6.

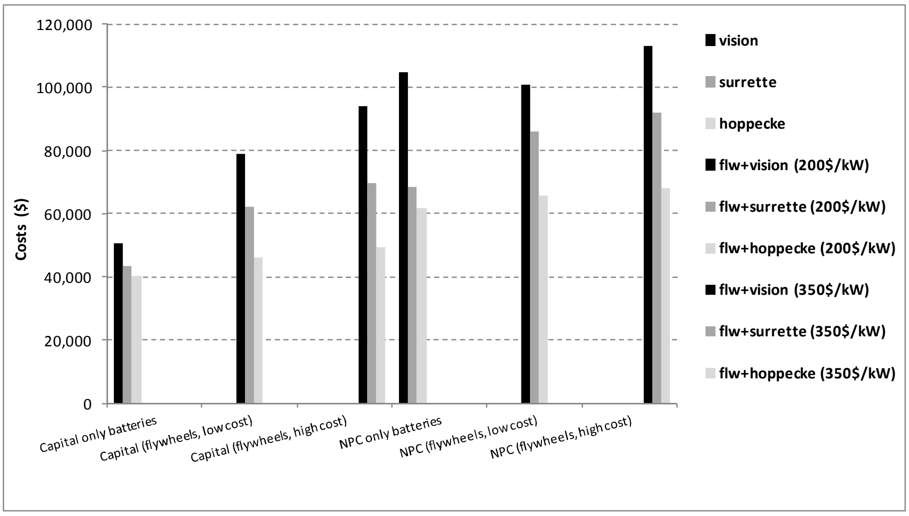


Figure 6.6 Capital and Net Present Costs of each system.

Initially the capital costs of systems with electrochemical batteries are lower than systems with flywheels because the materials used for both low- and mid-cost flywheel construction are very expensive. However, the final decision on a profitable investment has to take into account the NPC of the systems. An investor can take advantage of the higher flywheel lifetime and Figure 6.6 shows that the NPC of the systems with flywheels is comparable to that of simple storage technologies. Moreover, Figure 6.6 shows that the low price flywheels (200$/kW) correspond to systems with NPC strongly comparable to that of more conventional systems using stacks of batteries for energy storage.

Finally, the cost of the produced energy is one of the main criteria used by an investor to decide the best scenario for building a hybrid RES-based stand-alone system based on advanced technologies. This energy cost is presented in Figure 6.7 for all the scenarios simulated.

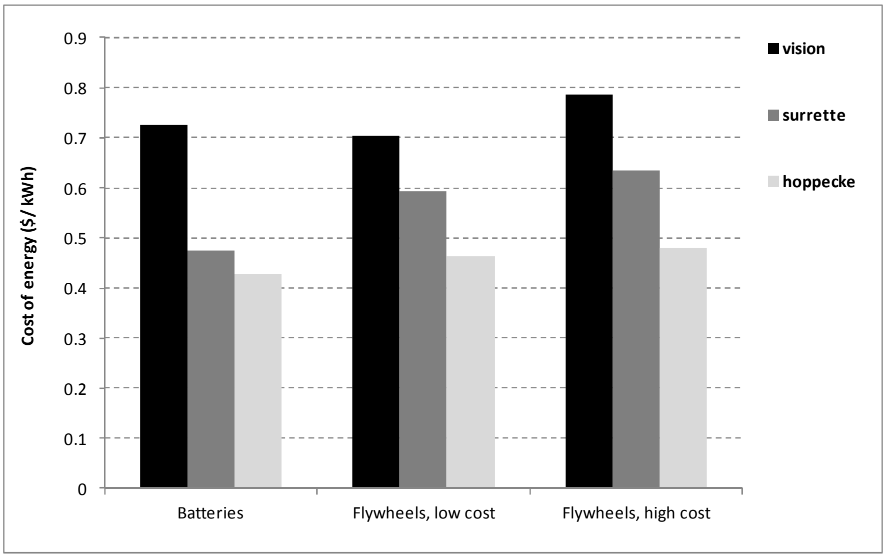


Figure 6.7 Levelized Cost of Energy of the systems.

General conclusion - Nine different RES based scenarios were simulated on Naxos Island, Greece. Three of them used electrochemical batteries as backup energy while the other six used a combination of electrochemical batteries and flywheel systems. Simulations were carried out using a modified hand-made calculation system and HOMER software. Electrochemical batteries as storage devices can be considered the "standard" solution for continuous operation of the RES based stand-alone systems. The use of flywheels in combination with classic batteries is proven to be feasible here, where it is shown that all the hybrid systems could cover the desired load of a typical house. Moreover, it is observed that although the initial costs of systems with simple batteries are much lower, systems combining flywheels can be competitive because the NPC of the different systems are equivalent. This is further strengthened by the systems' Levelized Cost of Energy, which is comparable and in some cases, when using flywheels, is lower. Finally, this innovative method of energy storage shows that flywheel systems could be commercialized in the near future.

6.3 Innovative Energy Storage for Off-Grid RES Based Power Systems: Integration of Flywheels With Hydrogen Utilization in Fuel Cells

Background – Developing the above innovative project further, special effort has been made for advanced technologies, such as flywheels in combination with hydrogen, to be integrated into everyday systems. For this simulation, specific loads of a typical house and a typical country house were taken into account, as Figures 3.8a & b present. Again, Naxos Island was assumed to be the installation location, selected due to its high RES-potential. In these hybrid RES based systems, the excess electricity necessary to charge the flywheel is produced either by a diesel generator or a hydrogen-fed PEM fuel cell. In the country house scenario, the excess electricity produced is sold to the Greek Public Power Corporation through a one-way grid connection at 0.60 $/kWh, since the desired load is lower than that of a typical house and thus allows a significant excess of produced power which increases the economic benefit of the project. This extremely high selling tariff arises from the contract signed between the Greek authorities and the owner of a project up to 10 kW, in accordance with Greek legislation. This price affects the annual amount of money spent during the annual operation of a hybrid system as these gains (from the sale) must be subtracted from the annual investment and operation and maintenance costs.

The project presented here is similar to the power plant established on Utsira Island, Norway (Nakken et al., 2006). The Norwegian system uses wind power to produce hydrogen which is then utilized in a PEM Fuel Cell. Batteries along with a flywheel supported by a synchronous motor are used as a back-up module for the coverage of ten consumers served by the micro grid. Conceptually, the main differences between the Utsira project and the system presented here are the design and use of the flywheels. In the Utsira project, flywheels are treated independently from batteries to stabilize the local grid rather than store excess energy. It is also important to underline the absence of solar panels (PV) in the design and integration of the Utsira Island system.

In terms of techno economics, the basic scope of this project is to investigate the feasibility of hydrogen usage in an already established system and to identify the operational differences between the specific loads for a typical house and a country house that must be covered by the same power system. Finally, the core point to be shown by this work is whether a totally environmentally-friendly RES based system is feasible without being supported by a grid connection.

Simulation process - To accurately finalize the simulation of the present project using the mathematical model presented in Chapter 2, the different variables should be selected carefully. The crucial parameters for the financial aspects of the present project are the lifetime of the specific power plant $N_{proj.} = 25\,\text{years}$, the nominal interest rate $i' = 4\%$, the annual inflation rate of $f = 1.6\%$ (the average price according to European Statistical Economical Data (http://epp.eurostat.ec.europa.eu)), and the cost of CO_2 emitted per ton $C_{perton} = 46.5\$$. The latter parameter is provided by the Kyoto protocol. After studying the local meteorological data to identify the most appropriate RES as presented in Section 3.2, the 12V DC system was designed to satisfy the requirement of efficiency maximization. During the system design stage, a hybrid photovoltaic-wind system was selected to cover the desired load. The next step was the development of a new storage system, equivalent to a battery-type storage unit but including flywheels, as described in Section 6.2. The HOMER software incorporated the flywheels in the form of load to be covered at each simulation step and does not provide the option to use flywheels as energy storage devices for excess electricity. This hybrid storage system is a combination of a flywheel, a DC-DC converter and an electrochemical battery (Hoppecke 3000 Ah). The specific type of battery was chosen because it offers great capacity at an affordable price and can be combined effectively with flywheels. A 10 kW high voltage flywheel was used in this scenario. The flywheel's main characteristics are the round trip efficiency (= 75.2%) and the maximum charge rate (= 3.926A/Ah), which is higher than the most powerful commercial battery (Perrin et al., 2006). The flywheel is permanently connected to a DC-DC converter for voltage regulation purposes between the devices (being necessary due to the DC current and parallel connection chosen), as shown in Figure 6.4.

Comparing the above system to that of Nakken et al. (2006), the present one has a hybrid back-up system unlike that of Utsira plant. The Norwegian power plant's flywheels are not connected with the batteries to operate as one compact hybrid storage system. Instead, its flywheel / asynchronous machine system is used separately as a grid stabilizer rather than as an energy storage system. Furthermore, solar energy is not used in the Utsira plant, thus a direct comparison between these projects underlines the differences between the selected approaches. Integration of the completed simulated systems was finalized through the electromechanical layouts as presented in Figure 6.8 and Figure 6.9. The figures present hybrid RES based systems capable of covering the load of a typical house and a typical country house using solar and wind energy sources.

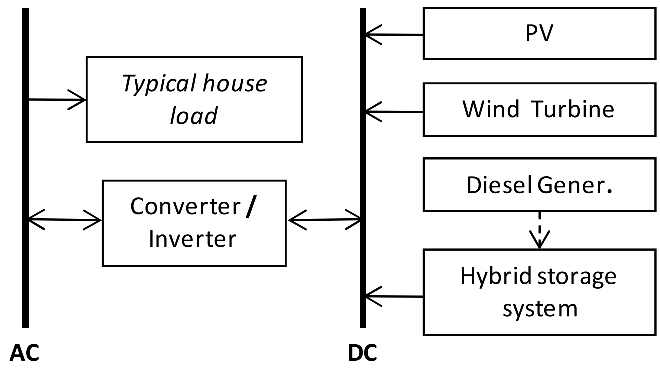


Figure 6.8 The components of the hybrid system with a diesel generator.

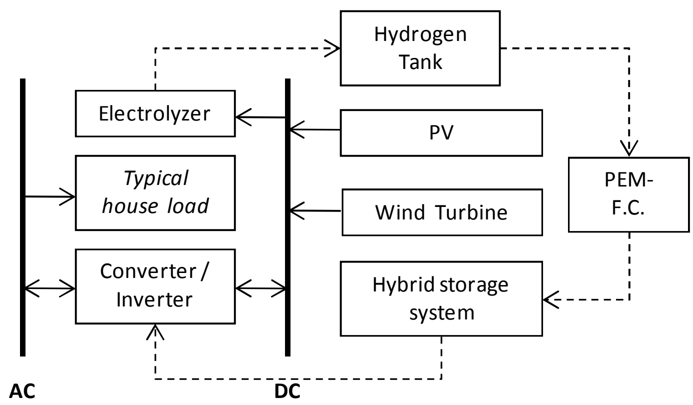


Figure 6.9 The components of the hybrid system with hydrogen technology.

However, the systems differ concerning the energy storage and grid connection as shown in Table 6.3.

Scenarios	Load (kWh/year)	System description
a1	7775 (typical house)	PV, Wind, Electrolyzer, Hydrogen tank, PEM FC, Hybrid storage system, one-way grid connection.
a2	2980 (typical country house)	PV, Wind, Electrolyzer, Hydrogen tank, PEM FC, Hybrid storage system, one-way grid connection.
b1	7775 (typical house)	PV, Wind, Diesel Generator, Hybrid storage system.
b2	2980 (typical country house)	PV, Wind, Diesel Generator, Hybrid storage system.

Table 6.3 Presentation of the different scenarios.

Scenario a2 uses a one-way grid connection only for selling the excess electricity and not for covering the load as a back-up energy source. The hybrid battery bank is charged by a diesel internal combustion engine (Figure 6.8) which could be replaced by a fully equipped system that uses hydrogen to charge the hybrid storage system (Figure 6.9).

To construct the most environmentally-friendly system, an ICE (http://www.directindustry.com/prod/cadoppi/gasoline-generator-sets-66301-585676.html) was directly compared to hydrogen technologies for charging the hybrid battery bank. This allows better management of the otherwise wasted excess electricity. It is important to note that the direct supply of electricity from the fuel cell has been avoided here due to the significantly increased costs of a high power PEM-FC (Barbir, 2005).

Besides the use of different technologies for the coverage of the hybrid storage system, the main difference between the ICE and the hydrogen systems, as presented above, is that the hybrid storage system of the second case (Flywheel with Hoppecke battery, see Figure 6.9) is not directly connected to a DC-bus, but to an inverter which provides the load to the typical house. This is crucial to allow the direct comparison of the ICE and hydrogen system, because the electrolyzer load should be covered exclusively by RES technologies. Thus, the load from the hybrid battery bank can be used only for the needs of the typical house and not for the electrolyzer.

All the systems considered were assumed to utilize solar and wind energy simultaneously while the desirable load for the charge of the hybrid storage system is covered either by a hydrogen-fed fuel cell or a diesel generator, for the sake of comparison. Actually, FESS technology incorporated here consists of a rotor suspended by bearings inside a vacuum chamber to reduce friction, and connected to an electric motor which can operate as a generator whenever necessary (Bolund et al., 2007). Specifications of the simulated devices are presented in Table 6.4.

Devices		Capacity	Capital costs	Lifetime	Reference
Diesel generator		1 kW	200 $	15000 hours	(http://www.directindustry.com/prod/cadoppi/gasoline-generator-sets-66301-585676.html)
Electrolyzer (except membranes)		3 kW	3200 $/kW	20 years	(Barbir, 2005)
Membranes		-	4800 $/kW	10 years	(Barbir, 2005)
Hybrid storage system	Flywheel	2×10 kW	6500 $/unit	30 years	(http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home)
	Hoppecke battery	2×3000 Ah		10 years	
Hydrogen tank		40 kg	1150 $/kg	25 years	(Barbir, 2005)
PEM-Fuel cell (except membranes)		5 kW	4000 $/kW	Project lifetime	(Kolhe et al., 2003)
Photovoltaic		1 kW	3000 $/kW	30 years	(Kolhe et al., 2003)
Wind turbine		1×5 kW	32500 $/unit	15 years	(Duffie & Beckman, 1980)

Table 6.4 Specifications of the simulated devices.

The devices used here, with the exception of the hydrogen-related equipment, are the same as those previously presented (Section 3.2) for Naxos Island, and their efficiencies are presented in Table 6.5.

Device	Efficiency (%)	Reference
Converter / Inverter	≥94	Generally known (typical)
Diesel Gener.	≈35	(http://www.directindustry.com/prod/cadoppi/gasoline-generator-sets-66301-585676.html)
Electrolyzer	70	(Barbir, 2005)
Hybrid storage system	75.2	(http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home.)
PEM-FC	40	(Wilkinson, 2010)
PV	13	(Kolhe et al., 2003)
Wind Turbine	30 (of the blowing wind energy)	(Duffie & Beckman, 1980)

Table 6.5 Efficiency per device.

Regarding the economic parameters, attention was paid to the lifetime of each component, which does not affect the energy calculations. Moreover, the electrolyzer and fuel cell do not have the same initial and replacement costs at the end of their life, because only the membranes are replaced and not the entire apparatus (about 60% of their initial cost (El-Sharkh et al., 2010). The lifetime of an electrolyzer is classified as 20 years (Table 6.4) while the lifetime of membranes has been estimated at 10 years. The costs of the entire hybrid storage unit (Table 6.4) arise from the standard cost of the batteries in combination with the average price between 200 $/kW and 500 $/kW of the flywheels. For this reason, and because CO_2 emissions are also included, the economic study was finalized by hand-made calculations without using HOMER software. The software was used to specify the system's energy calculations while the costs were calculated separately for each component and then summed to obtain the final budget. Finally, the lifetime of each battery, converter and flywheel was set to be 10, 15 and 30 years, respectively.

Methodology - The selected technical characteristics of the apparatus used is presented here together with the methodology followed for the energetic and financial optimization of the system.

The efficiency of inverters/converters was obtained from the technical data sheets published by their manufacturers (http://www.gosolarcalifornia.org/equipment/inverters.php). The mass of the diesel consumed by the diesel generator can be found from the combination of the fuel's density and the consumption of a typical diesel generator (lt/kWh) (http://www.cumminspower.com/www/common/templatehtml/technicaldocument/SpecSheets/Diesel/na/d-3425.pdf.) and by using the HHV for diesel (= 44.8 MJ/kg ≈12.5 kWh/kg) (NIST). Therefore, the energy produced can be calculated easily.

The values for the DC electrolyzer used in the present study are based on the technical characteristics of a HOGEN PEM Electrolyzer which produces 1.0 Nm^3/h of hydrogen and consumes 6.6 kWh/Nm^3 (≈73.95 kWh/kg) (Barbir, 2005). Typical industrial electrolyzers have electricity consumptions in the range of 4.5 and 6.0 kWh/Nm^3, which means that efficiency varies from 65 to 75% (Barbir, 2005). Accordingly, the value of 70% (Table 6.5) was selected for the current project, being representative of this hydrogen technology. PEM fuel cell efficiency varies between 34 and 40% (Wilkinson et al., 2010) while the lifetime of the membranes is 12,000 hours before replacement is required. The remaining parts of the device (cables, gauges, metallic parts, etc) are of endless life, i.e. their lifetime has been set equal to the duration of the whole project (Wilkinson et al., 2010).

Finally, the efficiency of PV and wind technologies used in the simulations can be found in the HOMER technical libraries (http://www.nrel/gov/HOMER). This software uses several types of PV panels and several wind turbines with specific pre-defined characteristics. The values used in the present study are presented in Table 6.5.

All the values used are within the allowable ranges with a maximum variation of ±5%, which is lower than the total error produced by the HOMER simulations. Therefore their accuracy does not affect the final results significantly.

Results and general discussion - The proposed system (see Figure 6.9) was first validated against the simulation of a power plant based on a PV-generator, wind turbine and hydrogen technologies, which has been installed and studied in Morocco (Panahandeh et al., 2011). This is the only available system using solar and wind energy sources together with hydrogen and a battery storage system. This validation was performed only in terms of energy due to the limited economical data available. The results of the Morocco plant were reproduced here using the HOMER platform and local meteorological data (http://eosweb.larc.nasa.gov/sse/).

For the given load and the combination of equipment in the DC-coupled configuration of the above system (Panahandeh et al., 2011) (which is compatible with the configuration proposed here), the energy production was found to be 22,418 kWh per year and the excess electricity 11,172 kWh per year. The above values, for the energy production and the excess electricity, are not shown in the original cited work (Panahandeh et al., 2011) but this is not a drawback since the objective of the validation was to re-construct an already established system and to replace the battery-based storage system with the innovative hybrid storage system (Figure 6.4), to evaluate the power of the proposed configuration.

It was found that the amount of energy required for the continuous operation of the system is 3,060 kWh per year, which could be used to charge the storage system. The equivalent amount of hydrogen that could be produced by this excess energy is 215 kg. As can be easily calculated using the typical efficiencies of each device (see Table 6.5), this amount of hydrogen is produced by 10,928 kWh of excess energy when a total of 11,172 kWh are available. Consequently, the scenario is proved feasible and the innovative configuration presented here allows easier exploitation of the excess electricity and lower energy losses. It must be noted that the amount of energy that should be supplied from/to the energy storage bank (batteries plus hydrogen) in the Moroccan power plant is 3,060 kWh per year and its energy losses are 7596 kWh per year, corresponding to 67.9% of the available energy excess, since the total input of the storage energy devices is 3,576 kWh per year (Panahandeh et al., 2011). For the system proposed here this figure is only 2.18% (244 kWh per year, see Figure 6.9), thus underling the significant reduction of energy waste due to the use of the hybrid storage system in conjunction with the innovative design used.

Following the validation and the obvious benefits of the innovative system applied to an existing power plant described above, the one-way connection of the hybrid storage system to a DC-bus was considered for the present project using different devices to satisfy the desired loads (for a typical house and a country-house). Since the system must be environmentally-friendly, the two-way grid connection should be avoided as it involves the use of polluting technologies. The minimum amount of energy that can be stored in the hybrid storage system for its continuous operation was covered by either hydrogen technology (electrolysis, hydrogen storage unit, PEM-fuel cell) or a diesel generator depending on the scenario, without the use of RES components. Each scenario was divided into sections that were simulated separately, while their energy parts were combined to produce the final results.

To further understand the energy results, four different scenarios were examined: a1 and a2 with the hydrogen technology, and b1 and b2 with the diesel generator as shown in Figures 6.8 and 6.9. After optimizing the systems in terms of energy, Figure 6.10 shows that both scenarios a1 and b1 fulfill the requirements to cover the desired AC primary load for a typical house (=

7,775 kWh/year). Figure 6.11 shows that systems a2 and b2 cover the load of a typical country house (= 2,980 kWh/year) by using the same established technologies as the typical house's load; therefore the amount of excess electricity produced is higher because the desirable load is lower.

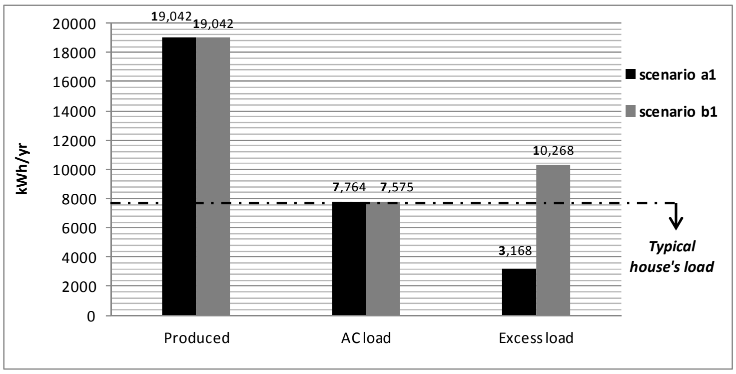


Figure 6.10 Produced, AC-primary and excess load for each system (load = typical house).

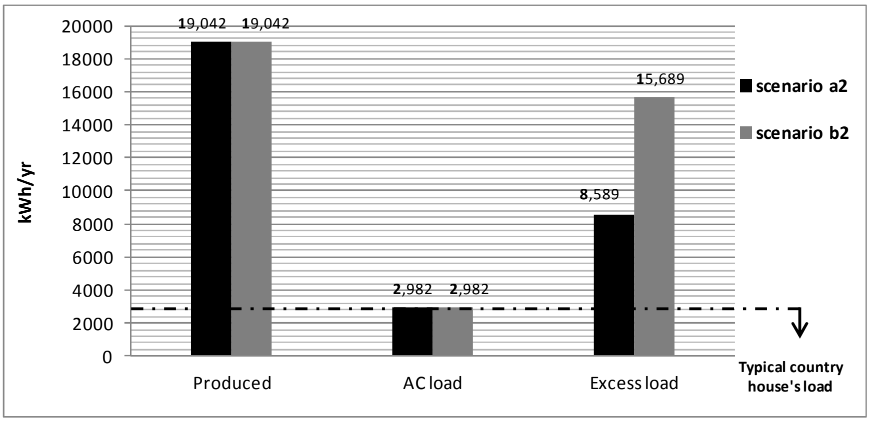


Figure 6.11 Produced, AC-primary and excess load for each system (load = typical country house).

Note that these specific simulated loads were designed after studying the electricity consumption of several appliances considered essential for the operation of a typical house and a typical country house. The amount of energy produced by both systems is the same; however, scenarios a1 and a2 utilize the excess load from RES based components more efficiently than scenarios b1 and b2 with the diesel generator. This occurs because both systems use the one-way connection of the hybrid storage system to a DC-bus, thus in scenarios a1 and a2 hydrogen is produced by the excess electricity, but in scenarios b1 and b2 the excess electricity is wasted. When a diesel generator is used in the system (scenarios b1 and b2), sales to the grid are not considered because the energy produced in this case is not “green”. Scenarios a1 and a2 represented totally “green” energy production, which is the only prerequisite for an energy producer to sell electricity back to the grid according to the contract between the Greek Public Power Corporation and the individual producer. Figure 6.11 also shows that scenarios a2 and b2 present the same results because the same peak load must be covered when the country house is being used.

The results from the HOMER simulation show that the annual electrical energy necessary to charge the hybrid storage system (= 2,890 kWh/yr) can be covered either by hydrogen technologies (a1) or by a diesel generator (b1), as depicted in Figure 6.12.

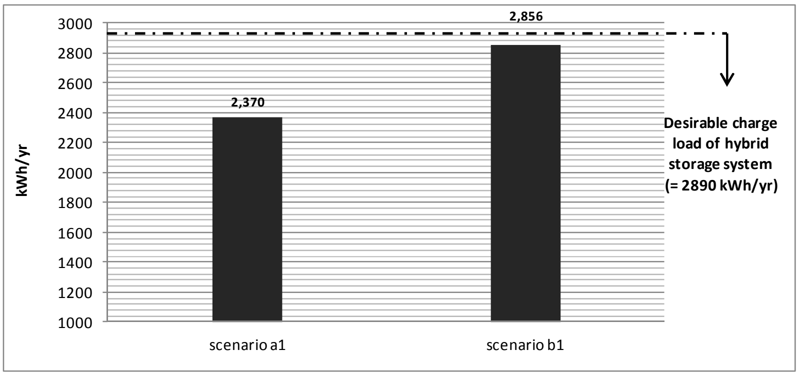


Figure 6.12 The desired annual electrical energy of the hybrid storage system using a flywheel with a Hoppecke 3 kAh battery.

Only scenarios a1 and b1 are significant since the other two use exactly the same technologies to cover a significantly lower load. Figure 6.12 shows the scenarios that use advanced technologies such as hydrogen and also use a combination of devices that marginally cover the desired loads (AC primary load and hydrogen load). In systems with diesel generators, it was found that 2,856 kWh/yr must be provided by the generator for more economical results. This small shortfall of scenario b1 to meet the storage system’s demands (=34 kWh/yr) is a negligible amount (1.2%) and is in the range of experimental error. Moreover, the quantity of energy within a hydrogen system is much larger (12%) because the benefit of selling energy back to the grid is higher compared to transforming this energy into hydrogen to cover the exact needs of the hybrid storage device. This percentage value is smaller than the sudden increase of the peak desired load (15%) defined for the purposes of HOMER simulation. Three steps are involved from hydrogen production to consumption, thus power losses increase and the electricity required to charge the hybrid storage system has to be one level higher than in the diesel generator system. However, for the hydrogen based system, the H2 load that can be stored is about 202 kg/yr.

The simulation results determined the average produced electricity value per hour per month and this value represents the percentage of the total production that can be used to predict the amount of excess electricity stored in the hybrid storage system. The energy produced can be transformed into hydrogen stored by the following approach: the energy needed to produce the total mass of hydrogen stored (kg) is the summation over one year of the energy produced in each month multiplied by the total energy that enters the hybrid storage system during the same month over the total energy produced. This amount must be finally multiplied by an efficiency factor defined by the rated consumption of a fuel cell over the rated power produced by this cell. For a typical PEM-fuel cell, the annual amount of hydrogen needed for the specific load considered here is 202 kg H2 (for a PEM-fuel cell: 0.035061 kg H2 / h corresponding to 0.5 kWh (Yilanci et al., 2008)). Although HOMER is the most accepted software package in the scientific community (Bernal-Agustin & Dufo-Lopez, 2009), finalization of the entire project using this tool was not fully performed because of the internal limitations (especially in terms of economics) of the overall simulation of each power system. Therefore, precise results can be obtained only by using external handmade calculations.

Another factor considered when comparing the two systems was emission reduction. The results of comparing the different scenarios for emissions are presented in Figure 6.13. Scenarios a1 and a2 present zero emissions, thus hydrogen technologies seem to be the most preferable. Scenarios b1 and b2 emit large quantities of CO_2 into the environment due to diesel consumption.

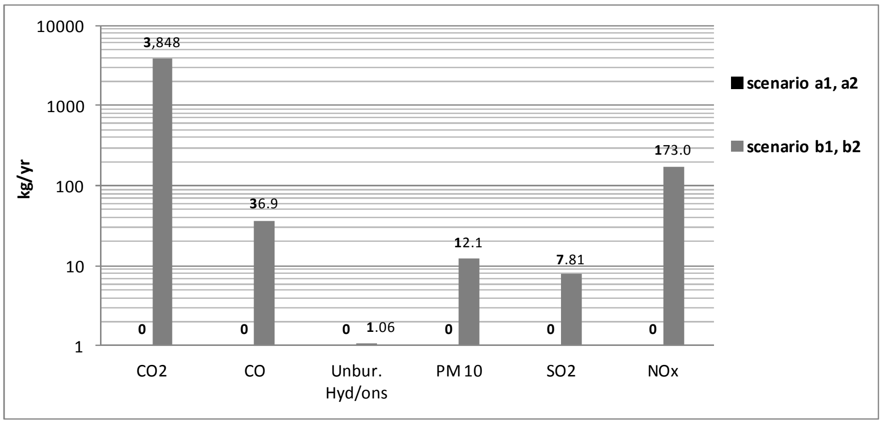


Figure 6.13 Comparison of the emissions per scenario. (Emissions for scenarios a1 and a2 are zero and emissions for scenarios b1 and b2 are identical).

The final step was to compare the scenarios in terms of economy. Emission costs as specified by the Kyoto protocol were taken into account to determine how the costs of the diesel generator system (scenarios b1 and b2) increase through time. The preferred power system would be that with the lowest initial and NPC costs. Figure 6.14 shows that the capital costs of the established hydrogen technologies (scenarios a1 and a2) are higher than those of the conventional diesel generator (scenarios b1 and b2).

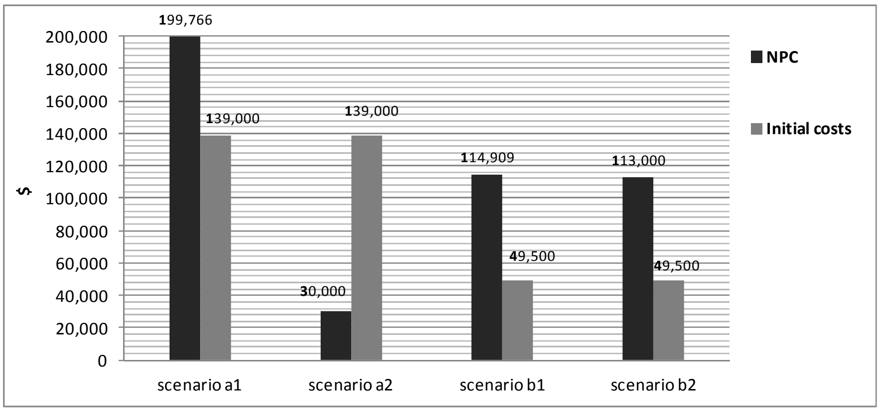


Figure 6.14 The initial costs and the NPC for all scenarios.

However, the same results are not observed in terms of NPC in any of this study's scenarios. Scenario a2 which incorporates hydrogen technology and covers the load of a typical country house, is capable of minimizing NPC by selling excess electricity to the grid, because the total load is smaller than in scenarios a1 and b1.

These estimates depend upon the project's lifetime, which in the present study is considered constant (25 years). Figure 6.14 shows that the initial cost of a system using hydrogen technologies is 65% higher than the cost of one using more conventional technologies. On the contrary, the NPC for scenarios incorporating hydrogen technology is 72% lower than that of more conventional technologies. This figure increases as the excess electricity not used by the typical country house in one year is sold to the grid.

The levelized cost of energy calculated by Equation 6.4 is depicted in Figure 6.15. The annual operating costs (Figure 6.16) represent the economic feasibility of each system.

$$\mathrm{COE} = \frac{C_{\mathrm{an.tot}}}{L_{\mathrm{prim.AC}} + L_{grid\ sales}},$$

where $C_{\mathrm{an.tot}}$ is the total annualized costs (€) of the system, $L_{\mathrm{prim.AC}}$ is the primary AC load of the system, and $L_{grid\ sales}$ is the energy (kWh) sold back to the grid.

Equation 6.4 Calculation of the levelized cost of energy in a system.

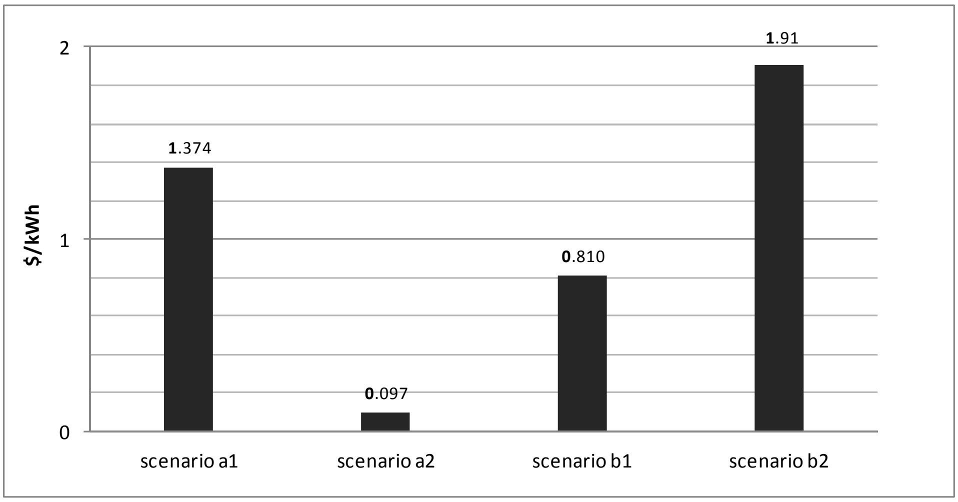


Figure 6.15 The Levelized Cost of Energy of each system.

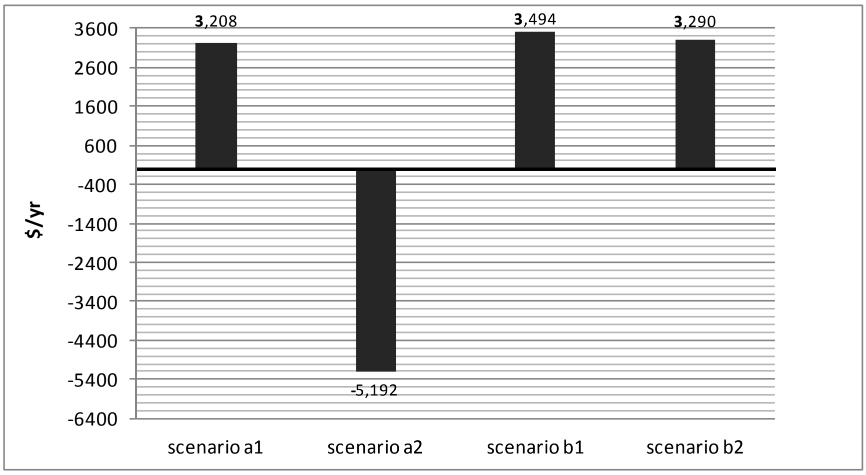


Figure 6.16 Operating costs for each system.

The results for hydrogen technologies presented in Figure 6.15 are very promising, although the NPC values of system a1 are rather higher than those of system a2, which covers the typical country house's load and gives excess electricity back to the grid. Accordingly, system a2 presents an 88% lower energy cost than system b1, a satisfactory result. The same comparison also applies to scenarios a2 and b2 for the same load coverage, where the system using hydrogen technology (a2) appears to be more economic for the given energy production. This difference in the energy costs between systems a2 and b2 is increased to 95%. The cost per kWh in system a2 is 0.097 $/kWh and this is directly comparable to that of the Public Power Corporation (0.10 $/kWh). Therefore, the economic aspects of this design also encourage the use of advanced technologies rather than conventional ones.

Further economic results are presented in Figure 6.16, where the annual operating costs are 8.2% lower in scenario a1 than in scenario b1, and system a2 provides substantial annual return. It should be noted that in scenario a2, the sum of -5,192 $/year is the clear profit for an investor after covering annual operating costs. Presently, diesel generator systems appear the most economically feasible, and only in specific circumstances is hydrogen technology used in totally "green" power plants.

General conclusion - Four different RES based scenarios were simulated for an off-grid power plant, assumed to be located on Naxos Island, Greece. The innovations of this project are the design of a novel hybrid storage device that comprises a flywheel and an electrochemical battery. The energy required for this hybrid device is provided either by a hydrogen-fed fuel cell or a diesel generator, thus allowing direct comparisons between state-of-the-art and conventional technologies. Simulations were carried out using a modified calculation tool incorporating HOMER software and handmade calculations. The use of flywheels in combination with batteries and hydrogen technologies is found to be feasible, as the simulations show that all the hybrid systems can satisfy the desired loads for both a typical house and a typical country house. The system comprising flywheels and hydrogen was found competitive against well-established technologies such as batteries and could be considered a unique solution for specific cases such as scenario a2. The use of such as system is further strengthened by its totally "green" character with zero CO_2 emissions. Finally, this study indicates that flywheel systems and hydrogen technologies can both be considered as alternative back-up energy options, at least for low-budget investments.

6.4 ON THE USE OF FLYWHEELS FOR ENERGY STORAGE DURING OFF-GRID ELECTRICITY PRODUCTION

Background – The aim of this research was to **construct and demonstrate** a totally eco-friendly apparatus for energy storage in several RES based systems.

This storage device is based on a rotating flywheel, spun by an electric motor run by the excess energy produced from RES-systems (PVs, wind turbines, etc.). Several questions can be asked about the system, and these are crucial for the development of such a project and the existence of FESS in the competitive RES market. How can a flywheel system be built? What is the optimal design (geometry) for the rotational mass in order to store the maximum possible energy? How does it operate under real-life conditions as a part of a stand-alone system? Is such an option feasible in terms of cost/benefit analysis? Under which conditions can these systems be feasible? Can a FESS be comparable with other mature, commercialized technologies used in small-scale applications?

To reveal the characteristics of flywheels during their operation and how their evolution could contribute to the problem of energy storage, the theoretical results should be validated against an established experimental laboratory-scale system. To promote FES systems into the global market, it is appropriate to collect real-time measurements from a purposely built, laboratory-scale FES system.

Theory - The design of such a device (especially the rotating mass) and the materials used for the flywheel's construction are crucial. Flywheel energy storage depends on these materials because a spinning rotor has an upper speed limit determined by the tensile strength of the material (Bleijs et al. 2000, Liu and Jiang 2007). For a given rotation speed, the amount of kinetic energy is determined by the rotating mass. Furthermore, the design characteristics should be selected taking into account both the operational parameters and the investment and maintenance costs.

The first step of the theoretical study is to calculate the torque of the electric motor, given as:

$$F_{motor} = \frac{\tau}{d},$$

where τ is the torque of the motor, and d is the distance from the rotational axis.

Equation 6.5 The torque of the electric motor.

The force exerted in a rigid body depends on the distance d of the particle from the rotation's axis. For the present calculations a cylinder was chosen, thus Equation 6.5 can be written as:

$$F_{motor} = \frac{\tau}{\int_0^r dr},$$

where r is the radius of the cylinder.

Equation 6.6 The rotational force offered by the motor to the rigid main body of the flywheel.

At this point it is necessary to identify the force of gravity which has to be overcome by the F_{motor} to rotate the obstacle at full speed. The differential volume of the cylindrical body is:

$$dV = rdrd\theta dl \ ,$$

where r is the radius of cylinder, l is its length, and θ is the angle covered during the rotational motion.

Equation 6.7 The differential volume of the rotated cylindrical body.

The differential mass of the cylinder is given as:

$$dm = \rho rdrd\theta dz \ ,$$

where ρ is the density of the construction material of the cylinder.

Equation 6.8 The differential mass of the rotated cylindrical body.

Finally, the force of gravity can be calculated as:

$$B = \int_0^r g\rho 2\pi rldr \ ,$$

where g is the gravitational acceleration.

Equation 6.9 The force of gravity.

By comparing Equations 6.6 and 6.9 it can be concluded that the cylindrical mass can be rotated at the full velocity of 188.5rad/sec which arises from the operational characteristics of the electric motor, as presented in the present Section at the next paragraph (Materials and methodology). When the gravitational force is higher than the force provided by the electric motor, the velocity will be reduced and its magnitude can be calculated as:

$$\omega_{new} = \frac{P_{motor}}{\tau_{mass}} \ ,$$

where P_{motor} is the power offered by the electric motor and is considered constant for each simulated project, and τ_{mass} is the torque that can be overcome during the rotation.

Equation 6.10 The new magnitude of the rotational speed of the rigid body.

Kinetic energy is a function of the moment of inertia and, as shown by Equation 6.1, depends on the rotational speed. It is necessary to compute the angular velocity ω_{new} for each case because it is one of the most important factors determining the feasibility of the FESS. Following an extensive energy analysis, a financial analysis is also necessary to reveal the feasibility of a FESS as well as the minimum requirements to be included in RES systems. The financial analysis is based mainly on the system's NPC as presented in Section 2.2.1.

Materials and methodology - To determine the feasibility of the above theoretical analysis, a laboratory-scale FESS was designed and constructed. An electric motor of 1hp was selected to be fed by the excess energy from RES technologies when the environmental potential fluctuates greatly. This electrical energy is transformed into kinetic energy and stored in a rotational mass. By following the reverse path it can be returned to the system via the electric motor that acts as an alternator. The power of the specific motor is determined by the power of the battery (approx. 660W) and the rotational speed (peak at approx. 1800rpm≈188.5rad/sec). Figure 6.17 presents the operational curve of the electric motor with no loads. The measured angular velocity is higher than that provided by the manufacturer because the standard value of 1800 rpm corresponds to standard supply voltage under the manufacturer's standard conditions, not those of laboratory experiments.

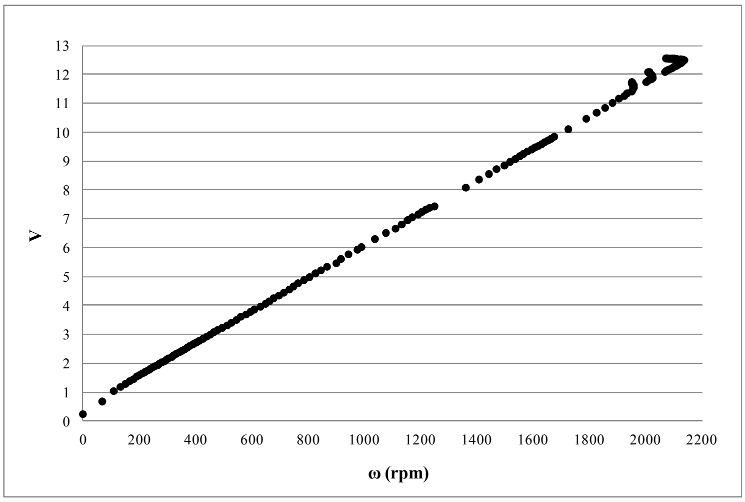
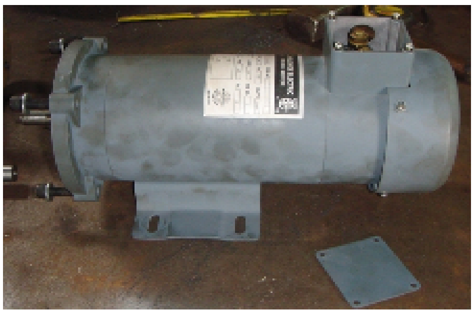


Figure 6.17 The operational curve of the electric motor with no load.

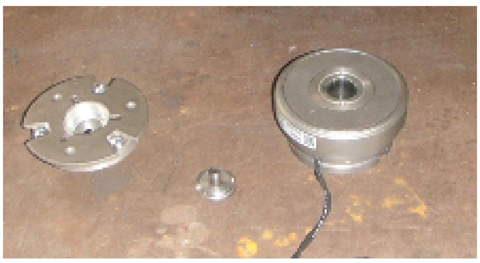
Hereafter, the highest rotational velocity is the same as the experimental velocity (approx. 2150 rpm), measured under 12V DC continuous supply without loads on the motor.

Several problems had to be overcome during the construction of the experimental FESS, mostly concerning the solidity of the rotational parts and the stability of the whole project. Numerous small-sized parts were designed from scratch. These parts are presented in Figure 6.18 and described in Table 6.6, and their final combination constituted an **innovative** venture. The majority of the system's parts were built in aluminum to reduce weight without affecting the design's compactness (see detailed discussion below). The crucial dimensional parameters were the thickness of the flywheel L, and the maximum and minimum radii of the hollow cylindrical mass. A detailed description of shape (compact or hollow) follows.


a.


b.


c.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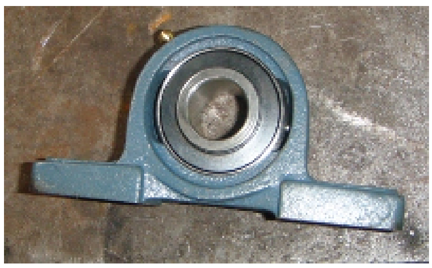
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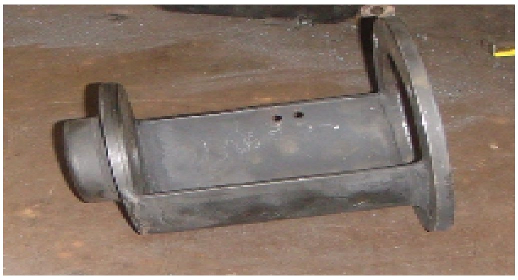

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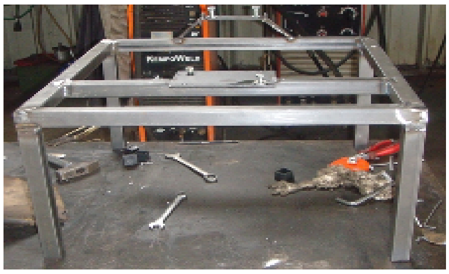


i.

Figure 6.18 The experimental apparatus (a) and its specific parts: (b) electric motor, (c) axle, (d) electromagnetic clutch, (e) roller bearings with housing, (f) adapter for axle, (g) adapter for rotational mass, (h) steel base, (i) frame.

Parts	Description	Quantity
Axle	Aluminum, 15 cm long, supports the rotational mass.	1
Bearing housing	Steel case, oil lubricated for the roller bearing at the end of the axle which is supported on the frame.	1
Adapters	Aluminum, one to adapt the clutch to the motor’s axle and one to permanently connect the rotational mass to the axle.	2
Electromagnetic clutch	Mayr ROBATIC, 24V, 20W and 20 Nm. Engages the rotational mass when necessary.	1
Roller bearing	Diameter of 0.02 m. Responsible for reducing friction losses during rotation.	2
Rotational mass	Stores the kinetic energy from the electric motor. Inner radius: 0.19m, outer radius: 0.25m, mass: 1.8kg, thickness: 0.005m and 8 connecting radii included (see Figure 6.19).	1
Steel base	Mounted onto the electric motor to keep the outer housing of the clutch stable for the rotation of the rotor mass.	1
Voltage source	Fed by the grid and offers 24V to the clutch during its engagement to the system: Phoenix Contact, 100V-240V AC input, 22.5-29.5V DC output.	1

Table 6.6 Description of the FESS parts.

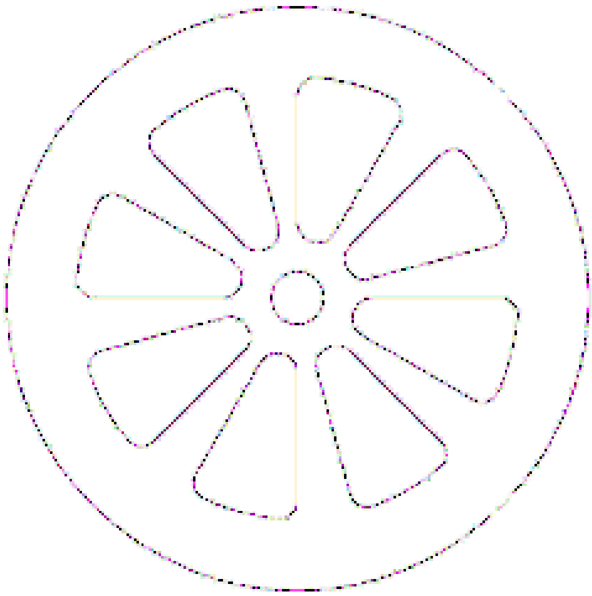
The calculation of the ideal hollow aluminum rotational mass is presented in Table 6.7, part (a). Although the thickness of L=0.0017 m calculated theoretically is the ideal thickness regarding weight and compactness of the rotational mass, it is considered dangerous because the vibrations caused will destroy the rotational mass and present significant safety issues.

ρ_{steel}	**7,874 kg/m^3**
$\rho_{aluminum}$	**2,700 kg/m^3**

	Part (a)				Part (b)	
Motor info	**Laboratory-scale**				**Building-scale**	**Industrial-scale**
P_{motor} (W)	745.69				8,000	100,000
ω (rad/sec)	188.5				733.04	628.32
Rotational mass dimension	**Solid steel**	**Solid aluminum**	**Hollow steel**	**Hollow aluminum**	**Hollow aluminum**	**Hollow aluminum**
R_{max} (m)	0.215	0.310	0.270	0.380	0.55	1.40
R_{min} (m)	-	-	0.235	0.325	0.49	1.31
m (kg)	1.940	1.390	1.600	1.070	2.054	11.766
ω_{rot} (rad/sec)	181.88	176.95	181.99	187.50	721.91	618.85
L (m)	0.0017				0.0017	
Operational results						
$E_{kinetic}$ (Wh) [from Equation 6.1]	0.207	0.290	0.317	0.473	27.720	720.902
I (kg m^2)	0.045	0.067	0.069	0.097	0.383	13.542
n (%)	0.0278	0.0389	0.0425	0.0634	0.347	0.721

Table 6.7 Simulated scenarios.

Therefore, dimensional characteristics of the cylindrical mass were altered as presented in Figure 6.19 and Table 6.8, and the final mass of the main rotational body was kept constant in order to be rotated under full angular velocity by the electric motor.



a.

b.

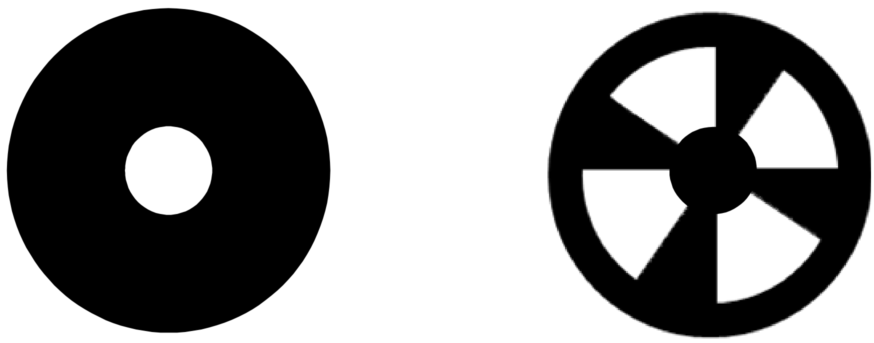
Figure 6.19 The rotational mass: (a) schematic design, (b) final construction.

One of the fundamental differences is the number and size of the connecting radii (eight instead of the four initially designed). This design eliminates the distortion of the rotational mass during rotation due to its higher thickness. The mass of the final construction was 0.700 kg heavier than the ideal because the adapter is also included with the axle.

Dimensional characteristics	Ideal rotational mass	Constructed rotational mass
R_{max} (m)	0.380	0.250
R_{min} (m)	0.325	0.190
m (kg)	1.070	1.800
ω_{rot} (rad/sec)	187.50	199.77
L (m)	0.0017	0.005
I (kg m^2)	0.097	0.064

Table 6.8 Ideal vs. constructed rotational mass.

Theoretical vs. Experimental Results and general discussion - The theoretical energy analysis, as presented above, was finalized for two different shapes of the cylindrical mass, as shown in Figures 6.20a & 6.20b for a laboratory-scale project.



a. b.

Figure 6.20 Theoretical rotational mass: (a) shape of solid cylinder, (b) shape of hollow cylindrical layout.

Given the 1 hp electric motor and using Equation 6.10, it is simple to calculate the torque provided at maximum power, which is approx. 3.956Nm. For each layout, two different materials were simulated to determine which could store the highest amount of kinetic energy as calculated using Equations 6.1 & 6.2. As Table 6.7 part (a) presents, the materials used for the simulations of the construction of rotational mass of a laboratory-scale FESS were steel and aluminum. The simulation process for several cylindrical masses in a small-scale project revealed that the layout of Figure 6.20b is the most suitable because it is lighter, has a larger radius, i.e. it can store more energy, and has higher efficiency, reaching 0.0634%. This value varies greatly from those presented by other researchers (e.g. Ledjef 1990, Kaldellis et al. 2009), however the latter are not supported by clearly presented calculations. In the present study, the above percentage is calculated by dividing the mean energy stored in a specific time interval by the energy consumed by the electric motor in the same period. This magnitude depends on the time-scale of the whole process. Thus, the value of 0.0634% corresponds to a one-hour time-scale and the flywheel can be rotated for less than one minute (see below). Therefore, it is preferable to limit the time interval to a few seconds in order to obtain higher efficiency values. Efficiency is calculated by dividing the energy output by the energy consumed by the electric motor, as shown in Table 6.7 part (a). This efficiency percentage is limited compared to that of batteries which can reach 75-80% during charge mode (Peter and Euan, 2008). Before changing the time-scale, it is essential to examine whether efficiency can be improved by changing the project's scale, therefore approaching a real-life scenario.

The cylindrical mass was simulated for two other scenarios and Table 6.7 part (b) shows that the highest efficiency obtained was 0.721%. It should be noted that the best result of the final choice of rotational mass has to be characterized by a balancing correlation between the cylinder's radius and length which determines the rotational speed necessary to maximize kinetic energy. Although the energy analysis study showed that an FESS cannot be promoted commercially due to its low efficiency, the final decision should be taken after performing a thorough financial analysis.

Table 6.9 presents the initial costs for each component based on local market research, their summation, and the NPC of each project. For small-scale projects, the capital costs and NPC required to build an FESS are high, therefore this is not a feasible investment. Large-scale projects are more promising and these systems appear to be more economically feasible compared to the use of common batteries. This difference can be attributed to the limited lifetime of batteries (4-5 years) compared to the unlimited lifecycle of flywheels.

Table 6.9 shows clearly that in an industrial-scale project, the NPC of an FESS is 73.98 % lower than an electrochemical storage bank of the same energy content. This can be even higher in large-scale applications because the installation of such a large electrochemical layout requires a spare room area with complicated air-conditioning systems to stabilize temperatures and operate the whole system with the same efficiency during its lifetime. However, it should be noted that at the end of its lifetime a battery is a major environmental pollutant, requiring special recycling treatment. On the other hand, an FESS constitutes a more environmentally-friendly solution for energy storage, especially when it is produced in RES-based stand-alone systems.

Batteries	**Small (laboratory) scale**	**Medium (building) scale**	**Large (industrial) scale**
12V/55Ah	1x180$	-	-
12V/100Ah	-	5x250$	63x250$
Charger/Controller	200$	1,000$	12,600$
Sum	380$	2,250$	28,350$
NPC	**524.39$**	**3,252.63$**	**40,982.95$**
FESS			
Electric motor	450$	1,000$	5,500$
Rotational mass	300$	400$	1,000$
Magnetic clutch	300$	600$	3,000$
Bearings	100$	200$	400$
Electronic parts	200$	300$	1,000$
Sum	1,350$	2,500$	10,900$
NPC	**1,327.77$**	**2,451.48$**	**10,661.22$**

Table 6.9 Financial comparison of the different technologies.

In a flywheel system, the duration of the rotational motion of the cylindrical mass is a crucial parameter for the estimation of the system's efficiency, to be more competitive against other storage options. Table 6.7 part b, shows that the industrial-scale FESS consumes 100 kWh and stores an average of 0.721 kWh. Under these circumstances its efficiency is 0.721%. This very low percentage can be increased by changing the rotational time. By decreasing the charging time step the energy consumed by the electric motor can be directly compared to that returned to the system through the reverse path by the rotation of the mass. Under these operational conditions and bearing in mind the financial results presented in Table 6.9, an FESS can rival competitive storage technologies widely available on the market, but only for applications that use a storage energy bank to support a system for a short time during its operation or to cover a peak load for a limited time during a single day such as UPSs.

The experimental process also demonstrated that an FESS can be rotated for about 40 seconds and then it stops due to friction losses because the apparatus is not vacuum-enclosed. In addition, the whole rotation of the axle is based on typical roller bearings with high friction losses compared to electromagnetic bearings. The efficiencies ranged between 83.78% and 8.75% and the operational time fluctuated from 2 to 13 seconds (Table 6.10), although the flywheel can be rotated for 40 seconds due to the inertia moment.

t (sec)	**ω (rad/sec)**	**E_{FESS} (kWh) [Equation 6.1]**	**Average E_{FESS} (kWh)**	**$E_{consumed}$ (kWh)** $\left[=\frac{745.69}{3600}t\right]$	**n (%)** $\left[\frac{Mean\,E_{FES}}{E_{consumed}}\right]$
1	199.77	0.000357		0.000207	
2	194.05	0.000337	0.000347	0.000414	83.78
3	186.97	0.000313	0.000336	0.000622	54.02
4	179.49	0.000288	0.000324	0.000829	39.09
5	172.11	0.000265	0.000312	0.001036	30.13
6	164.94	0.000244	0.000301	0.001243	24.19
7	158.26	0.000224	0.000290	0.001450	19.98
8	151.86	0.000207	0.000279	0.001658	16.86
9	145.75	0.000190	0.000270	0.001865	14.45
10	140.58	0.000177	0.000260	0.002072	12.56
11	136.01	0.000166	0.000252	0.002279	11.04
12	131.20	0.000154	0.000244	0.002487	9.79
13	126.52	0.000143	0.000236	0.002694	8.75

Table 6.10 Experimental measurements.

Analysis for such long time periods is meaningless because the angular velocity of the flywheel decreases to under 126.5 rad/sec for t>13 sec, thus the motor can return voltages lower than 12V (see Figure 6.17). By assuming that the theoretical results in Table 6.11 vary at the same rates and do not differ significantly from the experimental ones, the angular velocity remains a constant parameter through time. The time-dependent efficiency presented in Figure 6.21 could be improved by using an electric motor of higher angular velocity that consumes the same amount of energy. The augmentation of the angular velocity will lead to the increase of stored kinetic energy in the rotational mass. Obviously, efficiency decreases with time due to friction losses, while the theoretical estimations are always higher than experimental observations because rotational speed has been considered constant in the theoretical approach.

t (sec)	ω (rad/sec)	E_{FESS} (kWh) [Equation 6.1]	Average E_{FESS} (kWh)	$E_{consumed}$ (kWh) $\left[=\frac{745.69}{3600}t\right]$	n (%) $\left[\frac{Mean\,E_{FES}}{E_{consumed}}\right]$
1	199.77	0.000357		0.000207	
2	199.77	0.000357	0.000357	0.000414	86.22
3	199.77	0.000357	0.000357	0.000622	57.48
4	199.77	0.000357	0.000357	0.000829	43.11
5	199.77	0.000357	0.000357	0.001036	34.49
6	199.77	0.000357	0.000357	0.001243	28.74
7	199.77	0.000357	0.000357	0.001450	24.63
8	199.77	0.000357	0.000357	0.001658	21.56
9	199.77	0.000357	0.000357	0.001865	19.16
10	199.77	0.000357	0.000357	0.002072	17.24
11	199.77	0.000357	0.000357	0.002279	15.68
12	199.77	0.000357	0.000357	0.002487	14.37
13	199.77	0.000357	0.000357	0.002694	13.26

Table 6.11 Theoretical results.

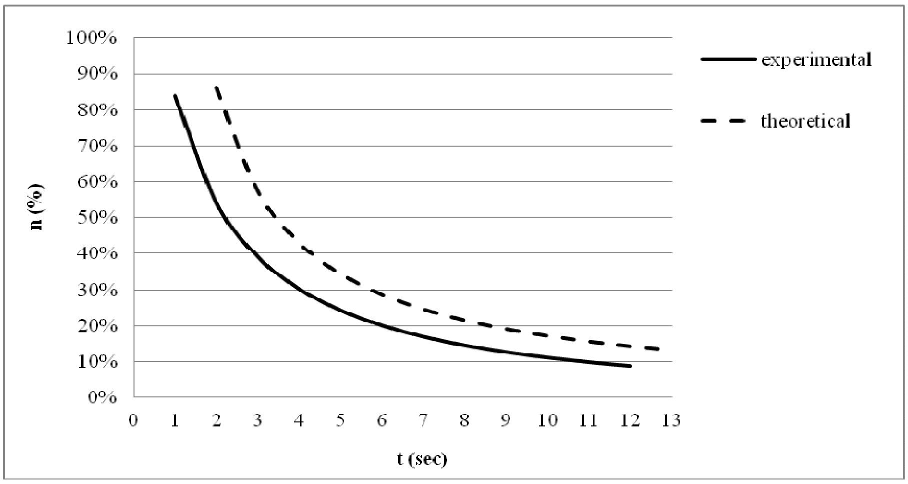


Figure 6.21 Theoretical vs. experimental curve of efficiency as a function of time.

General conclusion - An FESS was simulated under different scenarios, and one of which (laboratory-scale) was implemented to validate the theoretical analysis. This process revealed the outstanding characteristics of flywheels. More precisely, two different materials and shapes were simulated for the rotational mass. It was proved that a hollow aluminum cylindrical mass is the preferable option since it can give better energy storage results. This mass shape was incorporated into three different scaled projects to investigate the feasibility of an FESS compared to electrochemical batteries. It was found that the scale of the project is a favorable parameter for its implementation feasibility. Experimental apparatus was designed and built to validate the theoretical results. It was proved that FESS can be promoted as UPS systems to cover the peak load of a system during limited time periods. The evolution of material science in combination with advanced control units are expected to improve flywheel systems and promote their role in fully supporting an off-grid, totally green power plant.

To summarize Chapter 6, the main drawbacks of existing buffering technologies were revealed and the study of the evolution of a new hybrid system was considered necessary. Four different RES based scenarios were simulated for an off-grid power plant, assumed to be located on Naxos Island. The innovations here were the design of a novel hybrid storage device that comprises a flywheel and an electrochemical battery. The required energy for this hybrid device was provided either by a hydrogen fed fuel cell or a diesel generator, thus allowing direct comparisons between state-of-the-art and conventional technologies. Simulations were carried out using a modified calculation tool incorporating HOMER software and handmade calculations. The use of flywheels in combination with batteries and hydrogen technologies was found to be feasible, as the simulations showed that all the hybrid systems can satisfy the desired loads for both a typical house and a typical country house. The system comprising flywheels and hydrogen was found competitive against well established technologies such as batteries. It can also be considered as a unique solution in several specific cases such as scenario a2 presented in Section 6.3. This is further strengthened by the totally "green" character of the system which has zero CO_2 emissions.

An FESS was simulated under different scenarios, and one of which (laboratory-scale) was implemented to validate the theoretical analysis. Two different materials and shapes were simulated for the rotational mass and it was proved that a hollow aluminum cylindrical mass was the preferable option since it could give better energy storage results. This mass shape was incorporated into three different scaled projects to investigate the feasibility of a FESS compared to electrochemical batteries. It was found that the scale of the project is a favorable parameter for its implementation feasibility. Therefore, an experimental apparatus was designed and built to validate the theoretical results. It was proved that an FESS can be promoted as UPS systems to cover the peak load of a power plant during limited time periods. The evolution of material science in combination with advanced control units are expected to improve flywheel systems and promote their role in fully supporting an off-grid, totally green power plant.

Box 6 Summary of innovative buffering technologies.

7 CONCLUSION

This chapter presents an overview of the above research study and clarifies the importance of Renewable Energy Sources in everyday life.

7.1 GENERAL CONCLUSION

This thesis deals with the decoding of RES technologies so they can be successfully incorporated into hybrid systems. Several simulated projects were assessed for their energy and financial feasibility using existing software simulations tools. One of the basic aims was to identify the grey areas in the operation of autonomous RES based systems using the theoretical analysis conducted in existing software and finally, to propose an innovative approach that predicts and optimizes a system's operation. An innovative buffering technology was then proposed to strengthen the eco-friendly and zero emission character of the system.

Combinations of RES technologies can lead to the establishment of a hybrid system which produces electric energy to support the national AC grid or can be supplied directly to AC devices for domestic use in small-scale projects. The most promising part of such applications is the design of autonomous RES based hybrid systems with a totally eco-friendly zero emission character, in remote locations where the national grid is expensive to be extended or the terrain is too rough.

Initially this thesis focuses on the simulation of different RES based hybrid systems. An already established system in Leicestershire, UK was simulated and optimized using the HOMER platform. It was found that this system can be transformed into a stand-alone almost totally "green" system and this can be achieved by applying an accurate optimization technique on the energy part of the system.

To prove the necessity of the energy optimization process in construction of an RES based application, three different small-scale scenarios in four Greek islands were examined. The simulations were finalized under a modified calculation system based on HOMER software. This action was chosen because the first project examined identified the weakness of the HOMER simulation tool in the energy optimization part which is the most important detail for the design of RES based hybrid systems especially for remote applications. The selection of the appropriate technologies has to be in accordance with the climatic conditions and the desired load to be covered, and optimization must be based on the energy part of a system.

For this reason the next part which follows investigates a technique for the optimization of hybrid RES based stand-alone systems from the energy aspect. The main aim is to model the energy balance during the operation of RES technologies in order to cover the electrical needs of a simulated project. This optimization technique contains some problematic points concerning the energy remaining in the buffering technologies. The presented optimization technique at this point can be characterized as an innovative approach to system modeling because the already existing simulation tools are based on the financial optimization of a "green" system.

To study several simulation techniques, a hybrid system based on photovoltaic and wind energy in combination with an electrochemical storage bank was chosen to cover simulated small-scale desired loads of a typical house, a typical country house, and a small company. Initially this process was finalized using HOMER software however the simulation revealed that this platform cannot successfully simulate the operation of the battery bank. The State of Charge of the electrochemical storage bank is about 40% in the majority of examined cases, thus indicating that the battery does not play significant role in load coverage. Served load cannot meet the primary load and the whole system fails for long periods of the year. To overcome this situation with HOMER, substantial over-sizing on the capacity of the technologies is necessary, however published real-time data reveal that undersizing is necessary.

A new approach was introduced. This approach is based on the accurate management of the storage bank using a specific mathematical model that was designed and then applied. The new approach was found to produce simulations in excellent agreement with experimental results.

After the above process it was clear that the necessity of buffering systems in RES-based hybrid systems is a major issue however they must be made more environmentally-friendly before being incorporation into already established projects. The main drawbacks of existing buffering technologies were identified and the evolution of a new hybrid system was considered essential.

For this reason, four different RES based scenarios were simulated for an off-grid power plant, assumed to be located on Naxos Island. Here, the design of a novel hybrid storage device comprises a flywheel and an electrochemical battery. This allowed the direct comparison between state-of-the-art and conventional technologies and proved that the use of flywheels in combination with batteries and hydrogen technologies can be feasible. Moreover, the system comprising flywheels and hydrogen was found competitive against well-established technologies such as batteries and it can be considered a unique solution for some specific cases such as those presented in Section 6.3.

In the final stage of this research an FESS was simulated under different scenarios, and one of these (laboratory-scale) was implemented to validate the theoretical analysis the system. Throughout this process and compared to electrochemical batteries it was found that the scale of the project is a favorable parameter for its implementation feasibility. It was also proved that an FESS can be promoted as a UPS system to cover the peak load of a power plant during limited time periods. The evolution of material science in combination with advanced control units are expected to improve flywheel systems and promote their role in fully supporting an off-grid, totally green scenario.

7.2 FUTURE WORK

The research of this thesis could be extended initially by incorporating other RES technologies, such as hydrogen and biomass, into the mathematical modeling of the optimization technique presented here. This optimization process could also be embodied into an autonomous software platform which could be used to predict the operation and behavior of any RES based hybrid project built in a specific location. Moreover, this can be incorporated into the control unit of mobile applications that are based on RES technologies to predict their autonomy. Finally, one promising prospect derived from the present thesis is the combined operation of an FESS with RESs in an already established system. This process could present broad research opportunities to optimize such systems in addition with the evolution of the new hi-tech innovative materials.

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