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Cost-benefit Assessment of Nearly-Zero Energy House Generation and Consumption Matching Using Energy Storage

by

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Yesterday I was clever, so I wanted to change the world. Today I am wise, so I am going to change myself.

Rumi

Abstract

Over the coming years, electricity utilization management is becoming vitally important for all businesses and individuals. However, "supply follows demand" philosophy of the traditional electric power grid cannot be applicable for current costumers: On one hand renewable energy, particularly photovoltaic (PV) systems are increasingly used in buildings to cover the energy needs, and on the other hand the number of devices using electricity is quickly growing, leading to increasing energy consumption.

New solutions like smart grids and new technologies like energy storage systems are becoming necessary to solve this problem. Although, PV systems can help to make the costumers more independent from the grid, the balance between solar energy production and consumption can be mainly obtained with the help of the electric grid and energy storage systems. Despite this, determining the strategy that should be taken by the house owners to get the most benefits of these technologies and minimize the overall cost is the major challenge.

In this research work a cost-benefit analysis in a grid connected-house equipped with PV and energy storage is done. This analysis has two objectives: verification of the impact of dynamic pricing on the cost, and also verification of the impact of energy storage on the cost. For the first objective, the most common supporting policies for promoting renewable energies were assessed, including feed-in-tariff and net-metering, to calculate the cost. For the second objective the cost was calculated by considering an energy storage in the target residential house. In addition, different sizes of energy storage were considered to observer the impact of the capacity of energy storage system on the cost.

Keywords: energy consumption, photovoltaic system, support schemes, feed-in-tariff, net-metering, electrical energy storage

Resumo

Nos próximos anos, a gestão de utilização de eletricidade será cada vez mais fundamental para empresas e clientes individuais. No entanto, a filosofia da oferta a seguir a procura das redes elétricas tradicionais não se pode aplicar aos clientes atuais: Por um lado, as energias renováveis, em particular os sistemas fotovoltaicos (PV), são cada vez mais usadas em edifícios para cobrir as necessidades de energia; por outro lado, o número de dispositivos que necessitam de usar eletricidade está a aumentar rapidamente, levando ao aumento do consumo de energia. Novas soluções como as smart grids e novas tecnologias como sistemas de armazenamento de energia são cada vez mais necessárias para resolver este problema. Apesar de os sistemas PV poderem ajudar os clientes a tornarem-se mais independentes da rede, o equilíbrio entre a produção e o consumo de energia solar pode ser principalmente obtido com o auxílio da rede elétrica e de sistemas de armazenamento de energia. Apesar disto, determinar a estratégia a seguir pelos proprietários dos edifícios, para poderem retirar os maiores benefícios destas tecnologias e minimizar o custo global, é o principal desafio. Neste trabalho de investigação, é feita uma análise custo-benefício numa casa ligada à rede, equipada com PV e um sistema de armazenamento de energia. Esta análise tem dois objetivos: verificação do impacto de preços dinâmicos no custo e verificação do impacto do armazenamento de energia no custo. Para o primeiro objetivo, foram avaliadas as políticas mais comuns para promoção das energias renováveis, incluindo feed-in-tariffs e net-metering, para calcular o custo. Para o segundo objetivo, o custo foi calculado tendo em consideração o uso do sistema de armazenamento de energia na casa residencial em estudo. Adicionalmente, diferentes tamanhos de armazenamento de energia foram considerados para observar o impacto da capacidade do sistema de armazenamento de energia no custo.

Palavras-chave: consumo de energia, sistema fotovoltaico, esquemas de suporte, feed-in-tariff, net-metering, armazenamento de energia elétrica

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Chapter 1

Introduction

1.1 Motivation

Nowadays, energy has become one of the most important issues in the world. Among all the main consumers of the energy, buildings use the major portion. The energy consumed in buildings accounts for 40% of the energy used worldwide, and it has become a widely accepted fact that measures and changes in the building can yield substantial savings in energy [1]. Although, a lot of efforts have been done to reduce the energy consumption in buildings, the widespread use of electrical devices, to facilitate people's life and to increase the quality of life, such consumption is extremely increasing.

Electricity utilization management, over the coming years, should become a vitally important issue. The electric power grid has traditionally been built using a “supply follows demand ”philosophy, where the consumer has the right to demand any amount of electricity and pays a constant, pre-specified, and infrequently updated or reported price per kilowatt-hour of electricity consumed. With upgrades and improvements likely coming to the electric power grid in the form of “smart grids”, there is a near certainty that demand-sensitive pricing of electricity will soon become the standard pricing mechanism or tariff [2]. Although the house owner can manually try to manage their consumptions according to the dynamic pricing system to decrease the cost, it is not effective and some technologies to help them for minimizing the costs is needed.

Photovoltaic (PV) systems can be used to offer an opportunity to meet part of the daily energy requirements of the residential customer and make them less dependent on the electric utility companies and even make profit of that. However, the differences of balance between solar energy production and household electricity consumption must be ensured by the electrical grid. An overproduction in the day is sent into the grid and a demand in the evening is drawn from the electricity grid, using the grid as a virtual storage system. A next step will be to use local energy storage systems to store the produced electric energy during the day (lower consumption) to be used in the night (higher consumption) [3].

A lot of new business cases can be identified: households that store their produced energy do not request to their electricity provider any energy during periods of peak demand. In return they may receive a discount or a payment. A house can interactively work with the grid and trade with the power markets. They can buy from the grid during the cheap periods and stores the energy in the storage to use it later when it is needed. They can sell the extra stored energy to the grid during the expensive period. Although this provides economic advantages, it raises the complexities to the daily life. They have to make dynamic decisions according to the available services and even with real-time pricing, the variety of the consumption and generation and the capacity of the storage.

In this work the cost-benefit analysis in this complex model of energy-houses to find a balance between production and consumption, or even go more forward and make some benefits from it is going to be studied.

1.2 Research Problem and Objectives

The recent technology advances in photovoltaic systems, in storage devices (such as batteries), and smart grid technologies provide an opportunity to better manage the power in buildings in order to satisfy the demand in buildings with a minimal cost.
However, joint scheduling and management of such complicated system with intermittent local power generation, variable energy consumption and limited storage systems is nontrivial due to the following main difficulties:

- The interconnections and dynamics of the several electrical devices and systems in buildings are increasing and usually cannot be described by closed-form expressions. The practical solution would be simulation models. Performance evaluation of a joint schedule policy through simulation would be also very time-consuming.
- The scheduling and control policy has to be taken based on the current situation, but the main issue is that the action in the current stage may affect the future cost. Thus, a scheduling policy must consider the correlation among the actions at different stages.
- Both power generation and demand in buildings have a variable profile. It is caused either by environmental changes or by the changes in the human behavior. Thus, the performance of the management and scheduling policy can be evaluated only through the average over multiple sample paths.

In this research work the main aim is to improve the existing scheduling and management policy, which are used in practical systems. We will evaluate the scheduling algorithm by focusing on the impact of the storage size and tariffs. Accordingly the main objectives of this research work are:

- Study the impact of different tariffs on the overall cost of the grid-connected energy houses equipped with energy storage and PV. This study can be done using our own scheduling algorithm or an existing algorithm.
- Study the impact of energy storage on the overall long term cost in the grid-connected energy houses equipped by the energy storage and PV.

Chapter 2

State of the Art

In this chapter the background is going to be reviewed. First of all, the photovoltaic systems, its usage growth during the last decade, and the concept of building integrated photovoltaic systems are studied.

Then, the issue of energy demand in buildings and residential places. Then the energy storage and the issues which are related to this area will be reviewed. Next, it is studied the concept of energy houses that are connected to grids and are equipped with photovoltaic systems to get benefit of renewable energies, and energy storage to balance the generation and consumption of energy. At the end the concept of energy management system is reviewed and the works have been done to improve the performance of such systems.

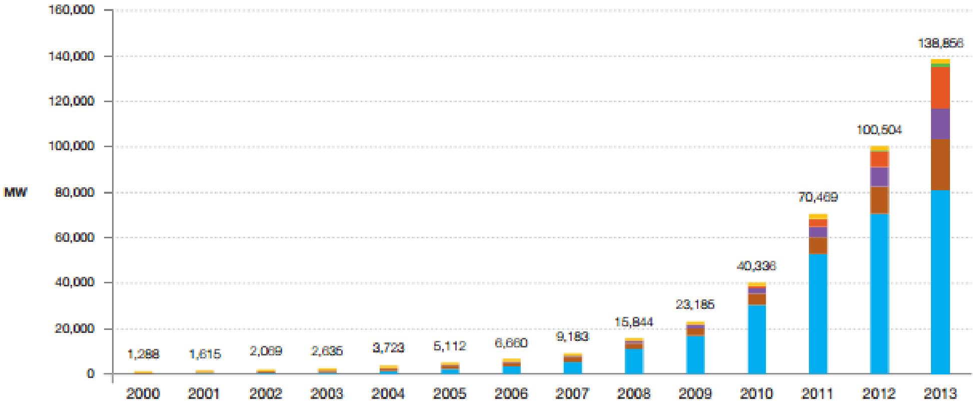
2.1 Photovoltaic (PV) and Buildings-Integrated PV

The world is currently facing two particularly important trends: one of them is rising fossil fuel prices and another one is concerns about climate change. Both create strong incentives for energy conservation and cleaner generation. Thus, the interest in renewable energy resources has grown. One of the most promising renewable energy technologies is photovoltaic. There are various research studies conducted on renewable energy applications, specifically solar energy field and their integrations with the utility grids. Moreover, photovoltaic (PV) systems have received the most attention due to their environmental friendly power generations, technological advances in panel efficiencies, easy installations, and financial incentive programs. In literature, both technical and economic impacts of the PV systems are investigated [4].

From the first PV applications, which were used in the space till now, more than 40 years have passed. In the late 1970s, the U.S. Department of Energy (DOE) began sponsoring projects to advance distributed PV systems. By the 1980s, companies such as General Electric, had developed PV systems prototypes, but technical challenges and high costs slowed the commercialization of these products [5]. Then more stakeholders pursued the blending of PV devices with building materials. In 1993, DOE initiated a program called Building Opportunities in the United States for PV to help commercialize BIPV products [6]. Then, some programs were established by some groups in Europe and Japan [7]. Today, partnerships among PV manufacturers, architects, and building-materials suppliers intend to address barriers and bring new cost-competitive products to the market. One of the first U.S. homes with BIPV was built in 1980.

Over the last decade , PV technology has acquired the potential to become a major renewable source of power generation for the world. As the figure 2.1 shows, the amount of the energy generated has increased rapidly. At the end of 2009, the world's cumulative installed PV capacity was more than 23 GW. One year later it was 40.3 GW and at the end of 2011 it was 70.5 GW. In 2012, the 100 GW mark was reached and by 2013, almost 138.9 GW of PV had been installed globally —an amount capable of producing at least 160 terawatt hours (TWh) of electricity every year. This energy volume is sufficient to cover the annual power supply needs of over 45 million European households. This is also the equivalent of the electricity produced by 32 large coal power plants. The global cumulative installed capacity could have even reached 140 GW in 2013 if the additional 1.1 GW in China were taken into account. Europe remains the world's leading region in terms of cumulative installed capacity, with 81.5 GW as of 2013. This represents about 59% of the world's cumulative PV capacity, down from 70% in 2012 and about 75% of the world's capacity in 2011. Asia Pacific countries are growing fast, with 40.6 GW now installed. Next in the rankings are the America's (13.7 GW) [8].

Since the main consumption of the energy is in the building sector (in Europe it is more than 40% of final energy use [9]), the Integration of renewable energy sources, particularly photovoltaic technology in this sector has been growing in the last decades. It has become



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
🟨 RoW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,098
🟩 MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	80	205	570	953
🟥 China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,600
🟪 Americas	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,727
🟫 APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
🟦 Europe	129	265	399	601	1,306	2,291	3,289	5,312	11,020	16,854	30,505	52,764	70,513	81,488
Total	1,288	1,615	2,069	2,635	3,723	5,112	6,660	9,183	15,844	23,185	40,336	70,469	100,504	138,856

FIGURE 2.1: Evolution of global cumulative installed capacity (from 2000 to 2013) [8]

a widely accepted fact that measures and changes in the building can yield substantial savings in energy. The incorporation of the photovoltaic system into the building could be a proper way to meet a portion of its energy consumption. The integration of photovoltaic systems into the building envelope is generally called as Building Integrated to Photovoltaic (BIPV). The PV modules can serve dual function of building skin, replacing conventional building envelope materials and power generation. BIPV uses photovoltaic panels in the place of traditional building materials in building structures such as roofs, windows, and facades. Photovoltaic panels are designed into many new construction projects, but they can also be fitted on pre-existing buildings.

2.2 Energy Demand

Although significant improvements in energy efficiency have been achieved in home appliances and lighting, the electricity consumption in the European Union household has increased by 2% per year during the period of 2001 till 2011 ,despite the numerous policies and programs to promote energy efficiency at EU and national level [10]. Some reasons are associated with that such as an increased degree of basic comfort and level of amenities and with the widespread utilization of new types of loads. Figure 2.2 shows the average daily consumption for the typical household in Europe.

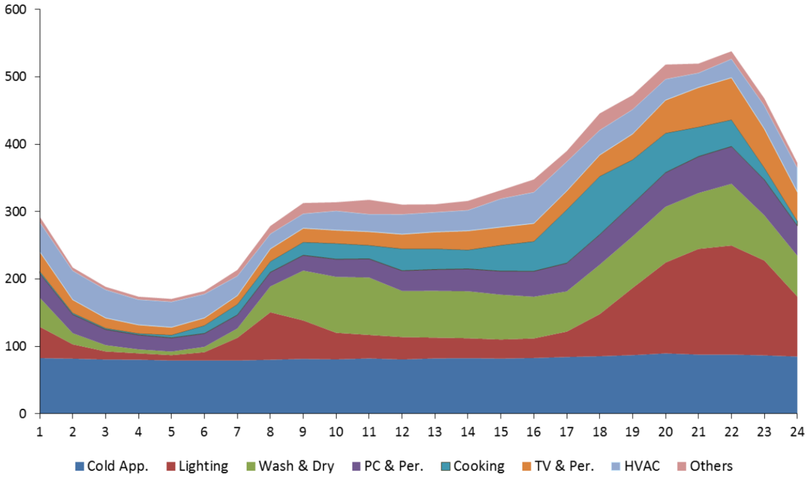


Figure 2.2: Electricity consumption for the average daily for the typical household in Europe[10]

Although generation of renewable energy is increasing all around the world, the challenges associated with meeting the demand and variation in demand are still important issues. In recent years, energy demand in the residential has become a crucial issue. For example, electricity used in France by this sector has reached 284 TWh, accounting for 65% of all electricity consumed in 2007 (434 TWh) [11]. We believe that this level of consumptions should be increased in the more recent reports. There are more than 79 million residential buildings and nearly 5 million commercial buildings in the United States of America, all of which together consume 70% of electricity in the country [12]. In China, since 1978 the energy consumed in buildings has risen from 10% to 25% of the overall energy consumption of the country, and is predicted to be 35% finally [12]. However, this situation continues to increase everywhere. Knowledge of energy demand profile and energy consumption of buildings facilitates the implementation of actions to reduce building operational costs. The dynamic behavior of the weather conditions and building operation, and the presence of multiple variables, requires the use of computer to model the energy demand in buildings. Several methodologies to estimate energy demand have been developed.

Many of the researchers translate changes in average temperature change on a daily, seasonal, or annual basis into heating and cooling degree-days, which are then used in building energy simulation models to project demand for space heating and space cooling. Building energy simulation is often done directly with average climate changes used to modify daily temperature profiles at modeled locations. Some researchers, directly incorporated changes in heating degree-days and cooling degree-days [13]. Other researchers have used econometrics and statistical analysis techniques [14]. In general, it is accepted that weather data can play an important role on forecasting energy demand in buildings. A normalized energy use index (NEUI) based on a temperature function is proposed in [15]. They discussed the influence of weather variables such as solar radiation and air velocity, and conclude that temperature is the most important factor on energy consumption. Their reasoning is that, since the equipment daily energy consumption is always the same, and because there is not significant variation of daily routine, changes in HVAC energy consumption is predominantly a function of temperature.

2.3 Policy Measures to Promote Renewable Power Supplies

It is obvious that energy demand is increasing and therefore greenhouse gas emissions are also increasing. It is a big threat for the world and using the renewable energies is the most important solution to eliminate this kind of crises. In order to reach to this valuable goal (reducing emissions of greenhouse gases and air pollutants and increase the share of renewable energy) a comprehensive perception is required.

Compared to conventional energy resources such as coal and oil, renewable energy resources are generally more environmentally-friendly and, therefore, benefit both the economy and the environment. Furthermore, because of the lack of renewable technology, the costs of developing and using renewable energy are usually more expensive and less competitive than costs of fossil fuel energy, especially electricity derived from coal burning power plants, in other words there is no enough natural incentive and security for the investors. Consequently the governments and policy makers have a vital role for arriving to this achievement. The interest in renewable energy became important as a policy measure after the oil crisis in 1970s. Since the oil shock in 1973, a lot of investments for research and development had been carried out. But most of these efforts did not lead to the introduction of renewable energy. Actually the promotion of renewable energy was initiated in the early 1990s, after the enforcement of the Convention for the Prevention of Global Warming. Many policies were introduced in the world to promote the utilization of renewable energy, different mechanisms have been applied in different countries to promote and encourage the use of renewable energies but among the all different applied policies, some of the them were significantly effective.

There is a fundamental problem in all support schemes: On the one hand, from an investor's point of view, support schemes as well as investment revenues need to be predictable and they need to be stable. On the other hand, from a policy maker's perspective, support schemes need to provide flexibility to adapt to changing circumstances. Thus, support schemes require some flexibility measures to be able to react to changing circumstances but in a predictable way without causing investors unnecessary insecurity.

An effective incentive policy must fulfill the following items:

- Provides tariffs for all levels, from domestic to large-scale developments
- Guarantees long term investment security
- Is administratively simple
- Is easy to explain in order to ensure public acceptance

It is the objective of the European Union to increase the share of renewable energy sources (RES) in our energy system. More precisely, the RES Directive 2009/28/EC determined binding targets of 20% share of RES in final energy consumption and a 10% minimum target for renewable energy in the transport sector by 2020 [16].

This part is going to introduce the most dominated support schemes such as feed-in tariffs (FIT), feed-in premiums (FIP), quota obligations, and tenders which have been done in Europe as shown in table 5.1. It should be mentioned that table 5.1 does not consider the secondary schemes such as Production Tax Credit, Tax Incentives and so on. The most frequently implemented support instruments in the European countries are feed-in systems.The number of countries using feed-in systems has increased steadily from 9 states in 2000 to more than 20 countries.

There are two available options in feed-in systems: First, **Feed-in Tariff** system, regarding to this support scheme, the government sets a fixed payment for each unit of electricity produced from renewable energy systems, and the distribution Company is obliged to buy the electricity along the pre-determined long-term contract which is usually 20 years. The U.S public regulatory policies act (PURPA) was the first to introduce the FIT policy since the 1970s, and the second implementation of FIT policy was in Denmark and Germany wich was in the mid of 1990 [17]. Long-term obligation for the buying the electricity is the main advantages of the FIT system which provides a certain investment environment and stable income flows for the generation units. The level of the feed-in tariff is typically determined by an administrative procedure, but it may also be estimated. If determined by the administration, the basis for the calculation in practice has mostly been the overall cost of a technology (levelised costs of electricity LCOE).

And second, **Feed-in Premium** system, In general, FIP can be evaluated similarly as FIT systems , but there is one main difference between these two support schemes. In contrast to FITs, plant operators have to market the electricity generated directly at the electricity market and receive an additional payment on top of the electricity market price. Figure 2.3 clarify the main difference. FIP model is implemented in the Czech Republic, Germany, Spain and Uk and some other countries in combination with FIT.

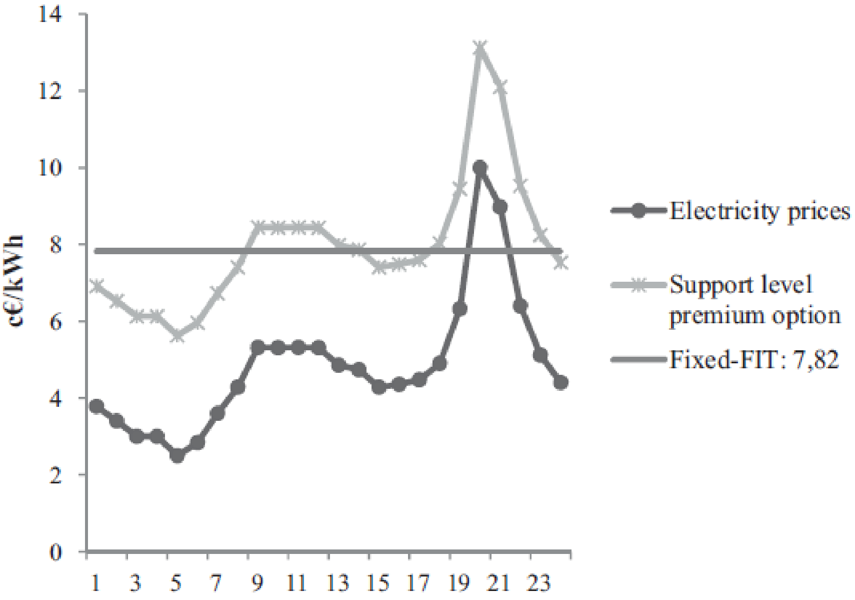


Figure 2.3: Difference Between FIT and FIP

93% of all wind onshore capacity and nearly 100% of all photovoltaics capacity installed by the end of 2010 in Europe were initiated by feed-in tariff systems. In most of the countries with significant PV deployment, the vast majority of installations have occurred following the introduction of a feed-in scheme. The strong growth in Germany and formerly Spain are the clearest indicators, but also tariff introductions in Italy, France, Portugal, Czech Republic and Slovenia have led to a strong stimulation of previously insignificant markets for PV.In Germany, the installed PV capacity increased from 1910 MW in 2005 to 17370 MW in 2010. Italy increased its PV capacity from 458 MW in 2008 to 3479 MW in 2010. In the Czech Republic, the capacity increased from 55 MW to 1953 MW from 2008 to 2010, in France from 104 to 1054 MW, in Greece from 19 MW to 205 MW in 2010 and in Slovakia from zero MW in 2009 to 144 MW in 2010[18].

Table 2.1: Diversity of RES-S Support Schemes in the Euro-28 (April 2014)

Country	Feed-in tariff	Quota obligation	Tender	Feed-in premium
Austria	✓			
Belgium	✓	✓		
Bulgaria	✓			
Czech Republic	✓			✓
Denmark		✓	✓	
France	✓		✓	
Germany	✓			✓
Greece	✓			
Hungary	✓			
Italy	✓		✓	
Netherlands		✓	✓	
Portugal	✓			
Slovakia	✓			
Spain	✓			✓
Sweden		✓		
UK		✓		✓

The **Quota Obligation** system, which is also referred as a renewable portfolio standard (RPS) or renewable energy target is applied in countries such as Denmark, Sweden and Netherlands in combination with other support schemes. It aims to support the renewable energy generation by increasing demand for renewable electricity. To do so, the amount of proportion of electricity supply that must be produced from eligible renewable energy sources is typically established through supply or distribution companies and is imposed on consumption. the implementation of an obligation system usually involves a penalty for non-compliance to ensure that obligates parties meet their renewable energy purchase obligations. The actual design of obligation systems may considerably vary depending on the economy or region to be introduced.

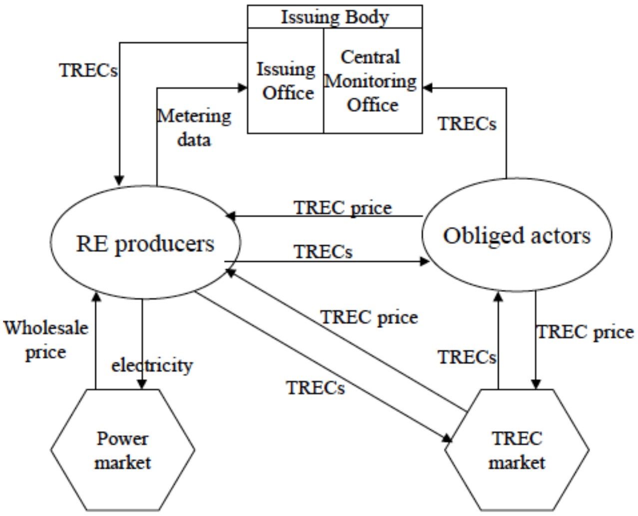


Figure 2.4: Flow chart of the main components of a TREC system [19]

The Obligation system often uses Tradable Renewable Energy Certificate (TREC) to simplify the burden of verifying compliance and to provide flexibility in achieving compliance. The TREC represents the value of electricity produced from renewable sources and allows sale of that benefit to be detached from the sale of physical electricity. The TREC systems can also simplify the regulators role in verifying compliance with the obligation system. Figure 2.4 presents a schematic representation of a typical obligation policy that uses TRESs for compliance verifications.

Under an obligation system, demand for TRECs is derived by increasing demand for renewable electricity from obligated actors. These actors will purchase TRECs either directly from producers or from the brokers. To verify compliance, obligated actors must retire or hand over the requisite number of TRECs, typically on an annual basis, to the monitoring authority. The TRECs will therefor attain a monetary value and provide an incentive for producers to produce them. In this way, the revenues for producers will be the sum of the price for physical electricity sold to the power market and the price for TRECs [19].

The main advantage of the obligation system are as follows: 1) encourage competition among renewable energy industries, and within the same industry; 2) compared to feed-in tariff, the burden on the government and consumers are relatively low; 3) the policy can specify the subject on renewable energy technology and easily control the competitiveness between the industries; 4) by combining green certificate trading, further cost reduction is obtained; 5) additionally, this policy does not compete with emissions trading. However, if the market is monopolized by one company or there is no potential of renewable energy resources physically, the obligation system does not work.

The **Tender Mechanisms** are promotion systems, which use an auction to determine the required remuneration levels. There are different types of tendering schemes used in the electricity sector to remunerate renewable power generation, with the remuneration price usually being the only or the most important evaluation criterion. The auction result can determine the premium of the full remuneration level. In recent years, European counties increasingly combined feed-in tariffs for small renewable systems with tenders for large installations.For instance, based on its existing feed-in-tariff scheme, France in 2011 included tenders for large-scale PV systems. The German Federal Ministry for Economic Affairs and Energy stated that the entire remuneration for ground-mounted PV installation shall shifted from feed-in tariffs to tenders [20].

2.4 Energy Storage

Electricity storage is playing a vital role in the electricity generation and delivery industry. All aspects of the industry need storage to help manage the electricity generation and delivery, especially in order to the integration of more and more renewable generation.

The energy, which is provided by renewable sources, is intermittent and variable. Energy storage technologies can smooth out this variability by allowing unused electricity to be stored for later use when generation capacity is low or electricity cost is high to meet demand. Also energy storage devices provide valuable solution to improve the stability, power quality and reliability of power supply. Electrical energy can be stored in mechanical, electrical, chemical or thermal forms and can be later converted to electricity when is needed.

Different energy storage technologies are in development in order to meet the challenges of practical power systems applications. Research and development in the field of energy production and storage has main targets obtaining of a high efficiency systems based on lower cost and longer life. Briefly, the energy storage system provides an advantageous disconnect between resource availability and utilization of the renewable energy.

In [21], it is studied the performance analysis and comparison of different energy storage devices in building energy systems in a micro-grid environment. The building energy system operation is formulated as energy cost minimization problem with storage devices and other devices in the system. The uncertainties in demand profiles and solar radiation are considered, and a stochastic optimization problem is formulated. The scenario tree method is applied to solve the problem. Numerical results demonstrate that the proposed method is effective in selecting the best combination and optimal capacities of the storage devices, and in obtaining the optimal operating strategy of each device in the building energy system. It is found that thermal storage units and water tanks are effective in saving energy cost in all scenarios, but the electrical battery may not be economical for use due to its high investment cost and short lifetime. Based on the above analysis, rules for selecting storage devices at a specific location can be determined. By comparing the simplified model of one scenario of the demand and solar radiation profiles to the multiple scenarios in the stochastic formulation they found that it would be sufficient in many cases to obtain the best combination of storage devices with the forecasted demand and solar radiation efficiently without using stochastic formation.

In summary, the development of storage systems can diminish dependency on fossil fuel and, ensure power quality and help to integrate intermittent renewable resources into the grid. Several types of energy storage technologies are used for those purpose. In following section, different types of electrical storage systems are described.

2.4.1 Mechanical Storage Systems

The mechanical storage system includes the pumped hydro system (PHD), flywheels and compressed air energy storage (CAES). For instance pumped hydro in the most widespread large-scale storage technology deployed on power systems.

2.4.1.1 Pumped Hydroelectric Storage

Pumped hydroelectric storage facilities store energy in the form of water in an upper reservoir, pumped from another reservoir at a lower elevation. A schematic view of a pumped hydroelectric storage (PHS) system is shown in Figure 2.5. The principle is generally well known: during periods when demand is low, these stations use electricity to pump the water to the upper reservoir. When demand is high, the water flows out of the upper reservoir and activates the turbines to generate high-value electricity for peak hours.

Generally, the pumped hydroelectric storage system is used in power plants for load balancing or peak load shaving. The height of the waterfall and the volume of water are two major determinant factors of storage capacity. Very long lifetime and practically unlimited cycle stability of the installation can be the main advantages of PHS systems and the need for a site with different water elevations is the main shortcoming of this technology.

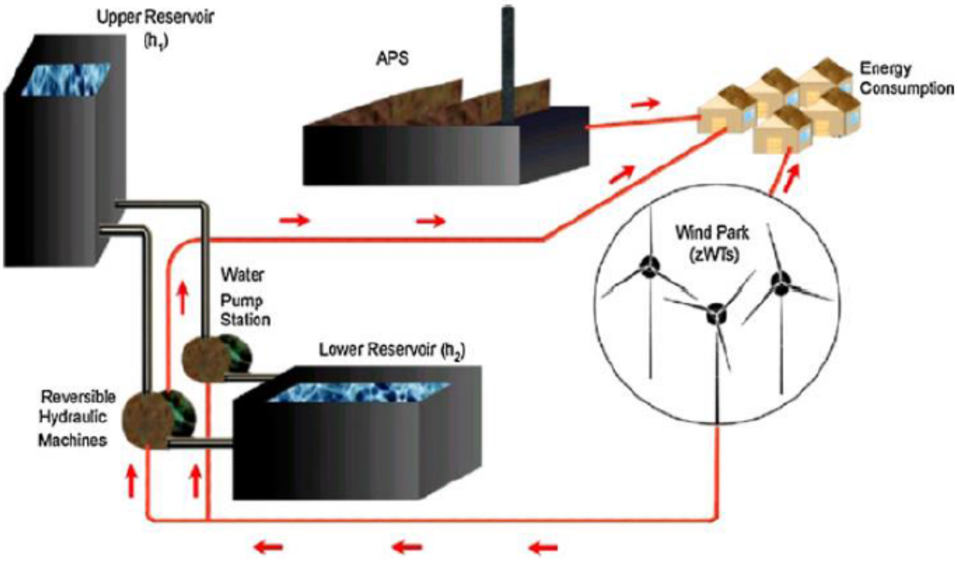


FIGURE 2.5: Pumped Hydro Operating Principals

2.4.1.2 Flywheel Storage System

Flywheels store mechanical energy that interchanges in form of electrical energy by means of an electrical machine with a bidirectional power converter. Flywheel energy storage systems (FESS) employ kinetic energy stored in a rotating mass with very low frictional

losses. Electric energy input accelerates the mass to speed via an integrated motor-generator. The energy is discharged by drawing down the kinetic energy using the same motor-generator. Figure 2.6 shows the components of the Flywheel energy storage system. Some of the key advantages of flywheel energy storage are low maintenance, long life , negligible environmental impact and high efficiency as well.
The materials for the flywheel, the type of electrical machine, the type of bearings all together determine the FESSs energy efficiency. [22].

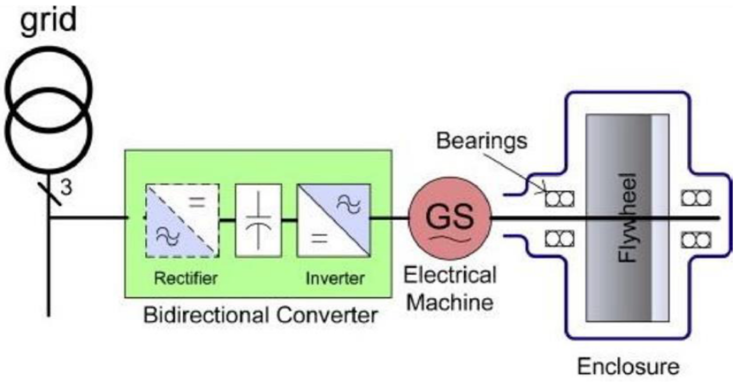


FIGURE 2.6: Components of the FESS

2.4.1.3 Compressed Air Energy Storage

Compressed air energy storage (CAES) is another technology to store energy. CAES plants are largely equivalent to pumped-hydro power plants in terms of their applications, output and storage capacity. However, instead of pumping water from a lower to an upper pond during periods of excess power, in a CAES plant, ambient air is compressed and stored under pressure in an underground cavern. This compressed air is used later to power a generator during peak periods when the energy is needed.[23].

A power plant with a standard gas turbine uses nearly two-thirds of the available power to compress the combustion air. Thus it is possible to use electrical power during off-peak hours in order to compress the air and drive the air into the underground storage vessel. Then when demand increases during peak hours, the air is moved to the surface and heated with clean burning natural gas to expand the volume and velocity. The air-gas mixture is used to drive a specialized turbine that can generate up to 300 MW of power. Since the off-peak electricity is used to compress the air rather than gas, a CAES plant uses almost less than half the amount of natural gas required by a conventional combustion turbine [24]. The whole general process is presented in Figure 2.7.

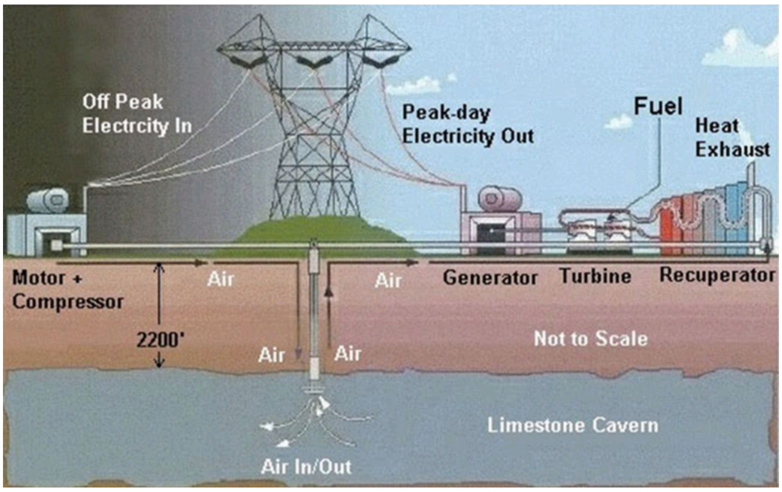


FIGURE 2.7: Illustration of compressed air energy storage [25]

Compressed air energy storage is achieved at high pressures (40 to 70 *bars*), at near ambient temperatures. Thus, large caverns made of high-quality rock deep in the ground, ancient salt mines, or underground natural gas storage caves are the best options for compressed air storage, as they benefit from geostatic pressure, which facilitates the containment of the air mass. [25].

Several projects ran in the world to construct CAES plants. Among all, two plants have been constructed in the world are quiet well known: one in Germany and one in the USA of 390 MW and 110 MW turbine capacities, respectively. The first storage station using an underground compressed air reservoir has been in operation since November 1978 in Huntorf, near Bremen, Germany [26]. In 1991, an American installation in MacIntosh, Alabama, began to deliver 100 MW of power for 226 h. The ambient air is compressed and stored at a pressure between 40 and 70 bars in a $2,555,000\ m^3$ cavern, 700 m deep in the ground. During summer, the system generates energy 10 h per day on weekdays. The company using this application partially recharges the cavern weekday nights and full recharge is done on weekends. The system is in use 1770 h per year [25].

2.4.2 Electrochemical Energy Storage Systems

Batteries are one of the most popular devices used for energy storage. There are two main battery concepts: redox flow and electrochemical(Table 2.2). Redox flow batteries are storage devices that convert electrical energy into chemical potential energy by charging two liquid electrolyte solutions and subsequently releasing the stored energy on discharge.

Electrochemical batteries store energy in electrochemical form creating electrically charged ions, the principle of work being based on chemical reactions between positive and negative plates. When the battery charges, a direct current is converted in chemical energy, when discharges, the chemical energy is converted back into a flow of electrons in direct current form. There are a number of electrochemical battery technologies that can be considered for energy storage: 1) Lead-acid; 2) Nickel cadmium; 3) Sodium sulphur; 4) Lithium ion.

Key factors of batteries for energy storage application are: high energy density, high energy capability, round trip efficiency, cycling capability, life span, and initial cost. Lead-acid batteries have been used more than 120 years in different applications and they are the most widely used rechargeable electrochemical device for small-medium scale storage. But, there are also another battery solutions promising for stationary energy storage applications. All have higher energy density capabilities than lead-acid batteries, but at present, they are not yet cost effective for higher power applications. It can be mentioned nickel-cadmium and lithium-ion batteries are both more suitable for electric vehicle applications, where high energy density can offset higher cost to some degree [27].

The best kind of batteries to use in a residential power system are Lithium-ion batteries as well, because of their desirable characteristics such as efficiency (over 90%), long life cycle, high energy and power density.

2.4.3 Electrical Energy Storage Systems

There are two common electrical energy storage systems: supercapacitors and magnetic superconductors. Supercapacitors or ultracapacitors, which are somehow similar to electrochemical storage systems, are new innovational systems used for energy storage. They store energy as electric charge between two metallic or conductive plates, separated by a dielectric medium, which can be charged by differential voltage applied across the plates. As the battery system, supercapacitors work in DC but they allow a much higher power and energy density. As a main advantage can be mentioned that they have a long life cycle the charge-discharge time is very short. They are suitable to be used as uninterpretable power supplies. The major problems with capacitors, similar to flywheels, are the short durations and high energy dissipations due to self-discharge loss. There are a large number of developers of capacitors/supercapacitors. The leading companies include SAFT (France), NESS (Korea), ESMA (Russia), PowerCache (Maxwell, USA), ELIT (Russia), PowerSystem Co. (Japan) and Chubu Electric Power (Japan), etc. [28].

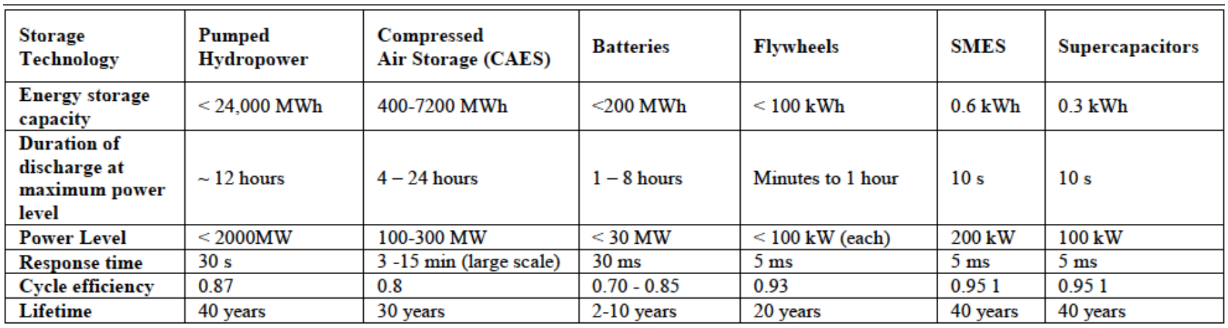
Superconducting magnetic energy storage (SMES) is an energy storage technology that stores energy in the form of DC electricity that is the source of a DC magnetic field. The stored energy can be released to the AC power system when it is necessary. The conductor for carrying the current operates at cryogenic temperatures where it is a superconductor and thus has virtually no resistive losses as it produces the magnetic field. The overall technology of cryogenics and superconductivity today is such that the components of a SMES device are defined and can be constructed. The integrated unit appears to be feasible for some utility applications at a cost that is competitive with other technologies. SMES is the only technology based on superconductivity that is applicable to the electric utilities and is commercially available today. In addition to today's power quality application, the historical development of SMES starting with the concept of very large plants that would store hundreds of megawatt hours of energy and were intended for diurnal load leveling are described. An advantage of this system is that the time for charge-discharge is very short, allowing a very high power to became available almost instantaneously.

2.4.4 Comparison of Energy Storage Technologies Suitable for Phtovoltaic Applications

No storage technology can currently address all applications. There are a wide variety of energy storage technologies and systems, which potentially are suitable for photovoltaic applications. These energy storages are listed in Table 2.2. The performance characteristic of these storage systems are different from each other: they may handle power ranging from hundreds of kilowatts (kW) up to about ten Gigawatts (GW); the charge/discharge time for these storage systems may range from seconds to minutes to hours; Power quality applications need fast-acting storage devices to respond to short unexpected interruptions in the power supply or sudden changes in the demand for power, while storage devices used for energy management must respond on a longer time scale and must store greater quantities of energy; cycle efficiency, which is defined as the ratio of energy delivered by the storage system to the load device to energy supplied by the power source to the storage system, and life time of the storage systems could differ as well. Briefly the following parameters characterize the performance of the storage systems:

- Energy Storage Capacity (commonly kWh or MWh)
- Duration of discharge required (seconds, minutes, hours)
- Power level (kW or MW)
- Response time (milliseconds to minutes)
- Cycle Efficiency (percentage)
- Life time and/or calendar life (years)

In Table 2.2 the main capabilities of different electricity storage technologies, are presented [30]. Moreover, an accurate evaluation of the value of electricity provided can be done by keeping into account the life-cycle cost analysis, that includes fuel, maintenance, depreciation and etc. In the case of photovoltaic systems there is low running cost because the “fuel” is sunlight, but an important source of cost, regarding depreciation parameter, for storage systems can be charge-discharge efficiency.



Storage Technology	**Pumped Hydropower**	**Compressed Air Storage (CAES)**	**Batteries**	**Flywheels**	**SMES**	**Supercapacitors**
Energy storage capacity	< 24,000 MWh	400-7200 MWh	<200 MWh	< 100 kWh	0.6 kWh	0.3 kWh
Duration of discharge at maximum power level	~ 12 hours	4 – 24 hours	1 – 8 hours	Minutes to 1 hour	10 s	10 s
Power Level	< 2000MW	100-300 MW	< 30 MW	< 100 kW (each)	200 kW	100 kW
Response time	30 s	3 -15 min (large scale)	30 ms	5 ms	5 ms	5 ms
Cycle efficiency	0.87	0.8	0.70 - 0.85	0.93	0.95 1	0.95 1
Lifetime	40 years	30 years	2-10 years	20 years	40 years	40 years

Table 2.2: Capabilities of Electricity Storage Technologies [30]

2.5 In-House Energy Model: Grid-Tie With Storage

Classically electricity storage for PV panels is mostly designed for stand-alone applications. In contrast, this work is focused on houses connected to the grid with the storage used to adapt part of the generated energy to the consumption needs within the day or the next days. In this way the house owner becomes less dependent on the grid. Figure 2.8 shows the main components of these systems. The "Grid-Tie With Storage" PV system incorporates one or more AC circuits which are not directly connected to the electric grid like the rest of the building, but are always powered through the inverter and/or charge controller. These circuits may supplies the whole house or power selected loads. The "dual function" inverter can supply the utility grid with any excess power produced by the system like the "grid-tie" inverter, plus the inverter works with the PV modules and battery bank (through the charge controller) to provide AC power to the backup circuits (for instance, when the grid is down). The charge controller manages the battery voltage, keeping them fully charged when the grid is live, and preventing them from being depleted when the system is drawing power from them. The main components of such houses are as follows:

- Solar Panels: It is made of solar cells, which is commonly called a photovoltaic cell. Most commercial solar cells are made of a thin layer of silicon. Sunlight is absorbed by the photovoltaic array creating direct current (DC) electricity. The solar panels can be mounted on the roof or on the ground.
- Inverter: The inverter takes the DC output and converts it to alternating current (AC). The AC output is then usable either in the building or elsewhere on the utility grid.
- House Power: It represents the electricity needs of the houses and household loads, such as lights, TV or washer, which use AC electricity.
- Battery Bank (Storage): Any excess power can be fed to a battery back-up system. This power can be the generated by the solar panels bought from the grid. The role of energy storage in an on-grid application is to store excess PV energy until it is needed.

- Charge controller: It protects the battery bank from overcharging or undercharging.
- Utility Grid: The utility grid acts as a bank - the power can be received from the grid, when the PV system is not producing enough power to meet the household's energy needs (in the winter, or during night periods, for instance). Also the extra power saved in the storage can be sold to the grid.
- System meter: It measures and displays solar system performances and status, such as how full is your battery bank, how much electricity your solar panels are producing or how much electricity is in use.

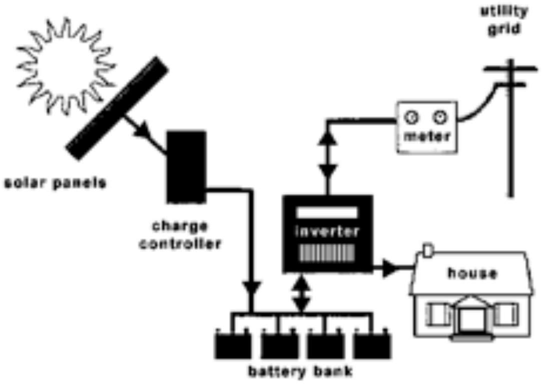


FIGURE 2.8: In-House Energy Model: Grid-Tie With Storage

2.6 Energy Management Systems

Building Energy Management Systems (BEMS) emerged after the energy crisis in the late 70's. This crisis combined with the fast growth of computer science has led to the energy management systems development. BEMSs aim to monitor and control the environmental parameters of buildings and at the same time to minimize the energy consumption levels and their associated costs. Nowadays, these systems become somehow commercial tools and are implemented in a wide range of applications, especially in large office buildings; thus useful experience is currently available regarding their benefits and drawbacks. In general, management systems comprise at least the following items: sensors to measure control variables; a controller able to carry out logical control operations or to provide control signals; actuator devices, which accept the control, signals and perform actions. Such an energy management system is presented in the figure 2.9. Controllers are typically computing elements, which implement the load management strategies via the control programs installed inside. The sensors take measurements, which constitute the principal source of information. Furthermore, to a certain extent, energy estimation models can be used instead of direct measurements, but these models are generally based on measurements [11].

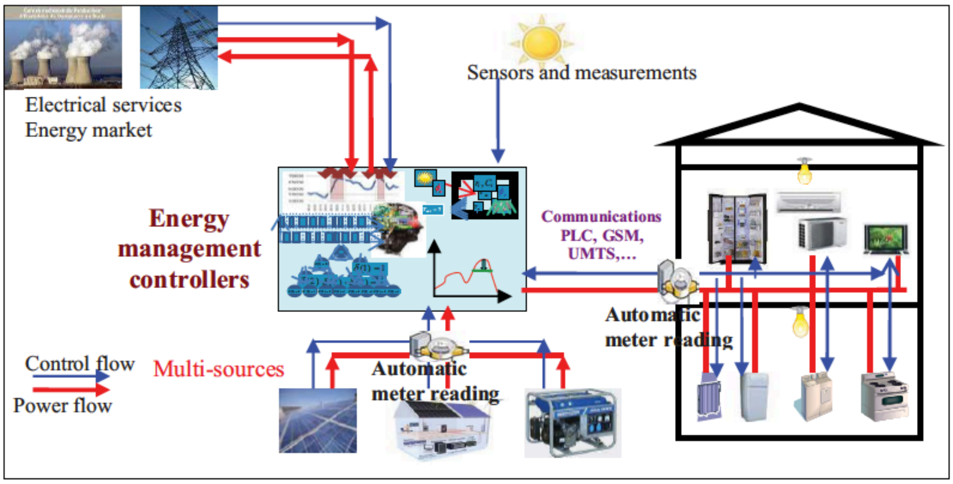


FIGURE 2.9: Energy Management System in Buildings [11]

The control strategy in these management systems has the following objectives:

- To satisfy the users preferences that are inserted into the system and to maintain thermal, visual and indoor air quality comfort based on guidelines of related bibliography [31, 32]. Users are a dynamic part of the building; therefore they should be taken into account in the control strategy. Latest trends in designing Intelligent Building Energy Management Systems (IBEMS) integrate a Man Machine Interface that could store the users preferences and adapt the control strategy accordingly [33].
- To minimize the building's energy consumption levels for heating/cooling and lighting.
- To supervise the whole operation of the system.

Most of the existing studies consider the schedule of individual systems. Some considered the joint schedule of both the demand and the supply of power systems. For example, Pfeiffer and Verstege considered short term unit commitment and load dispatch using mixed integer programming [34]. Illehaus and Verstege developed a dynamic search strategy to calculate the optimal unit commitment and economic dispatch of industrial facilities with CHP [35]. Guan et al. [36] have modeled the joint schedule of multiple power systems using mixed integer programming. And they used the scenario-tree method to handle the randomness in the model, which is not scalable unless appropriate scenarios are selected. However, the system models in these studies are usually simplified and in closed-forms to ensure simple evaluation and the above study only considers optimal strategies.

Though Markov decision processes (MDPs) [37], [38] provide general frameworks for many multi-stage decision making problems, the large state space and action space in practical systems usually make it impossible to find the optimal policies. There have been many attempts to solve large scale MDPs, for example state aggregation [39], [40], time aggregation [41], action elimination [42], [43], approximate dynamic programming [44], event-based dynamic programming [45], [46], and other simulation-based optimization models [47], just to name a few. Bertsekas and Castañon [48] developed the rollout method, which uses simulation to improve from a given base policy. When the total cost of an action, which is followed by the base policy in the future stages, can be accurately evaluated, the rollout method ensured to obtain a policy no worse and usually better than the base policy. The rollout method has been successfully applied to many problems such as quiz problem and its variations [49], the water resource management problem [50], and the wireless sensor network [51].

A joint schedule problem is considered to schedule solar power, wind power, combined cooling, heating, and power generation (CCHP), battery, and high temperature chiller in order to satisfy the load on electricity, sensible heat load, and latent heat load in buildings with the minimal average cost. The rollout method is applied to improve from given base policies through simulations. Numerical results show that the method obtains policies better than the base policies [4]. Different techniques are used in the literature to improve the performance of BEMSs. Some works tried to use the advantages of Fuzzy control techniques together with a man machine interface in satisfying the users' preferences. A fuzzy controller was developed and the minimization of energy consumption is achieved by the use of a suitable cost function for the whole system [11].

In residential level and in a dynamic pricing scenario, the use of automated Energy Management Systems (EMS) should be considered. This new intelligent EMS in a smart house has two parts, fuzzy part and intelligent lookup table. The fuzzy part is based on its fuzzy rules and inputs to make the proper output for intelligent lookup table. The second part, which its core is an associative neural network is able to map inputs to desired outputs. It takes two types of inputs, which come from fuzzy part and outside sensors. This system is able to find the best energy efficiency scenario in different situations [52].

Dariush Shahgoshtasbi proposes a three-level hierarchical control according to ISA-95 and applied to AC or DC micro grids [52]. This general approach of hierarchical control for micro grids is conceived for a large-scale power system, upstream in the utility grid hierarchy. Imitating the behavior of a grid synchronous generator control, the proposed hierarchical control strategy aims at balancing power between multi inverters coupled on the same bus without communication, while controlling the power at the point of common coupling (PCC) at the same time. This paper is related to urban areas with building integrated photovoltaic (BIPV) primarily for self-feeding of buildings equipped with PV arrays and storage. With the aim of elimination of multiple energy conversions, a DC network distribution is considered. The BIPV can supply a tertiary building at the same time as PV array may produce power through a hierarchical supervision able to exchange messages with the smart grid and metadata. The hierarchical control is designed as an interface to expand the system ability for advanced energy management control having regard to the grid availability and user's commands. It consists of four layers: human–machine interface, prediction, cost management, and operation. The operation layer, implemented in an experimental platform, takes into account the grid supply power limits and constrains the DC load. The experimental results validate the approach that may be a solution for the future smart grid communication between BIPV and utility grid [53]. Other work proposes an application for a heating control, which is based on the wireless sensor network (WSN) with techniques and advanced load management strategies for BEMS. Their application uses an innovative real-time control method that allows peak consumption to be reduced while maintaining thermal comfort [21].

The Energy Box is proposed as a 24/7 background processor operating on a local computer or in a remote location, silently managing one's home or small business electrical energy usage hour-by-hour and even minute-by-minute. It operates best in an environment of demand-sensitive real-time pricing. With energy box, virtually every electrical device in a home or small business will be controllable centrally. Energy Box has some important advantages: First, by delaying or pushing forward various uses of electricity (e.g. space conditioning), widespread use of the Energy Box could ‘shave the peaks and fill in the valleys of demand,’ thereby reducing the need for capacity expansion in electrical power generation and distribution; Second, the system should result in reduced electrical energy costs to the consumer; Third, the system supports local generation, storage and sale of electricity back to the grid; Forth, the system supports graceful reductions in power consumption by allowing voluntary partial load shedding as requested by the electric utility during times of extreme high demand; Fifth, requiring numerous minute-by-minute decisions over the course of a day, the system alleviates the home owner or small business manager from making such decisions, each only involving pennies but in the aggregate involving significant dollars. The primary integrating method of optimization and control is stochastic dynamic programming [15]

Chapter 3

Cost Calculation Methods

In this section, the methods for calculating the energy cost for the zero energy house is presented. The zero energy house, which is considered as a case study in this thesis consists of a PV system, a battery and electrical loads. The cost calculation is done for a given amount of consumption and production using the existing prices for buying and selling the energy.

In the very early stage of the analysis, the method to calculate the energy cost without considering storage system is presented. This calculation should be done to set the baseline of the assessment for the results while having an energy house equipped with storage systems. At last, storage systems with different sizes are included in the energy house and the cost is calculated accordingly. Moreover, some limitations are imposed on the amount of electricity that could be sold to the grid. In addition to feed-in-tariff policy, the cost is calculated using net-metering policy with and without an energy storage system.

The above calculations aim to show: 1) the effect of PV systems on the cost and benefit; 2) the effect of the energy storage system on the cost and the benefit; 3) the effect of the storage size on the cost and benefit, 4) the effect of the limitations that might be imposed by the government or energy companies on the amount of energy to sell; 5) difference between feed-in-tariff and net-metering policies. All these calculations are done without considering the cost of PV and storage systems including their prices, their installation cost, their maintenance cost, but the energy losses due to energy storage.

3.1 Cost Calculation Method without PV and Storage Systems

Each electric utility company charges a different rate for each kWh used. To calculate the cost of the energy in a very simple scenario, without PV system and energy storage and with a fix pricing system, the data needed to be determined is how many kilowatts are usually consumed in a house as well as the price charged for each kilowatt. The former data is calculated by the electricity counter installed in houses and the last one is defined in the energy companies. For instance EDP (Energia de Portugal) [54], which is the biggest energy company in Portugal, defines several tariffs.

Among the different tariffs presented in EDP, such as flat tariff and tariff with two or three time periods, consumers can select their desired tariff. Considering a very simple scenario, with the flat tariff, the average consumption cost during any period of time is calculated using the equation

$$ConsumptionCost = Consumption(kWh) * Price(kWhrate) \tag{3.1}$$

In the next step a little bit more complicated scenario is considered. Since the objective to benefit from existing dynamic pricing, the target of this study is the two-level tariffs which is presented in figure 3.1. Regarding this tariff, the energy price is 0.0946 €/kWh during the Off-Peak and 0.1785 €/kWh during On-Peak.

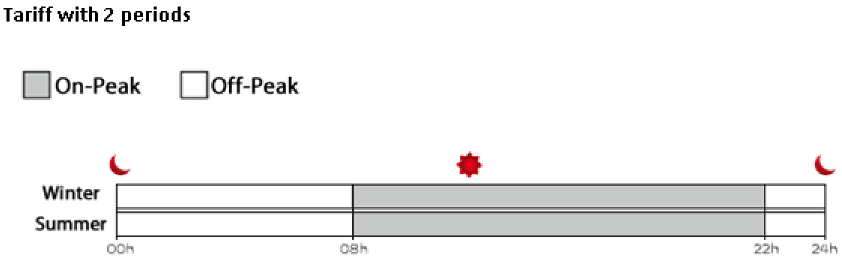


FIGURE 3.1: Electricity Price with Two periods Defined by EDP

It is needed to be emphasized this section just presents the methods and algorithms used to calculate the costs, so that the numbers presented for the tariffs will not be used in this section. The algorithms proposed in this chapter are perfectly adjusted for any kinds of tariffs.

As it was explained before, the amounts of energy consumed in different hours of a day are variable as well as the price of the energy. Thus, by considering a dynamic pricing system in the above house the equation is changed as follows for a specific day:

$$ConsumptionCost = \sum_{h=1}^{24} Consumption(h) * Price(h) \tag{3.2}$$

h represents an **hour** in the above formula. Accordingly the energy cost for a year is calculated with equation 3.3:

$$ConsumptionCost = \sum_{d=1}^{365} \sum_{h=1}^{24} Consumption(h,d) * Price(h,d) \tag{3.3}$$

h represents a specific **hour** and **d** represents a specific **day** in the above formula. The formulas, presented above, are general-purpose and can be used to calculate the annual cost of an electrical device or a commercial or a residential building.

3.2 Cost Calculation Method with PV System

The energy generated by the solar panels either is used directly by the electrical loads of the house or is sold (i.e. or transfered) to the grid. Different strategies might be taken in each hour based on the prices or according to the limitation made by energy regulations. In this section, both cases with and without limitation for sell are considered.

3.2.1 Feed-in-Tariff

In this strategy the decision at any time is taken based on the price of the energy for buying and selling in each hour of time. If the price to buy is higher than the price to sell, the generated energy must be consumed in the house and, since there is no battery to store the electricity, the remaining electricity should be sold to the grid network. In contrast, if the price to sell the electricity is higher than the price to buy, the energy produced by the solar panels should be sold to the grid network and the energy needed for the house should be bought from the grid. Obviously, this is valid just when there are no regulation or any kind of scheme to define a minimum level of self-consumption.

The above strategy is formulized in the Algorithm 1. In this chapter, all methods to calculate the cost are formalized into some algorithms. The algorithms calculate the cost for one specific hour. Prices for selling and buying are differentiated in these algorithms, except for net-metering policy, although their value might be the same in the actual tariffs.

Algorithm 1 Algorithm for Calculating the Cost in An Energy House With a PV System

```
Require: Consumption
Require: Production
Require: Price(B)
Require: Price(S)
Require: Cost
  if $Price(B) \leq Price(S)$ then
      $Cost \leftarrow Consumption * Price(B) - Production * Price(S)$
  else
      if $Production >= Consumption$ then
          $Cost \leftarrow -1 * (Production - Consumption) * Price(S)$
      else
          $Cost \leftarrow (Consumption - Production) * Price(B)$
      end if
  end if
```

The `Consumption` represents the amount of energy consumed in one specific hour. Accordingly, the `Production` represents the amount of energy produced by PV system, the `Price(B)` represents the price to buy energy, `Price(S)` represents the price to sell energy produced to the grid, and `Cost` represents the cost of energy in the same hour. The negative number resulted from the calculation refers to the benefit (in contrast to cost), which is earned from the PV system.

3.2.2 Net-Metering

Using net-metering policy, the energy needed for a house first should be supplied by the generated electrical power. If the amount of the energy generated is more than the amount needed, the remained energy could be sold (i.e. or directed) to the grid. Otherwise, the rest of energy needed for house must be bought from the grid. This is presented in the Algorithm 2.

Algorithm 2 Algorithm for Calculating the Cost in An Energy House With a PV System using Self-Consumption Strategy

```
Require: Consumption
Require: Production
Require: Price
Require: Cost
  if $Production >= Consumption$ then
      $Cost \leftarrow -1 * (Production - Consumption) * Price$
  else
      $Cost \leftarrow (Consumption - Production) * Price$
  end if
```

3.3 Cost Calculation Method with PV and Storage Systems

In this situation storage system is used to store the excess energy generated and return it to the system when the energy produced by PV is not enough for the house or the price to buy is more expensive. Some dynamic algorithms are presented in this section for an energy house equipped with PV and battery system. The algorithm is based on the capacity of the storage. In these algorithms, the efficiency of storage system is considered but all of the maintenance cost of the battery simply are ignored. As explained in the previous chapter, lithium-ion battery has relatively high efficiency (over 90%), but 90% is the number which is considered in these calculations.

3.3.1 Feed-in-Tariff With No limitation to Sell

The strategy used to define the algorithm is to store the excess energy produced to use later, when the price to buy the energy from the grid is higher. We believe this strategy leads an efficient result. First it is considered that the price to sell is higher than the price in peak hours. In this case it is always better to sell the excess energy produced because it leads to higher economic benefits. In contrast, if the price to sell is lower than the price of the energy during the peak hours, then it is always better to store the energy, as much as possible, during off-peak hours to use it during on-peak hours. The amount of the electricity that can be used from the electricity stored in the storage system depends on the storage efficiency. For instance, by considering 80 % efficiency for a given storage, there is a loss of 2 kWh for each 10 kWh stored.

The Algorithm 3 implements the above strategy. The `StorageCapacity` in the algorithm represents the overall capacity of the storage, which is fixed always; the `StoredEnergy` represents the amount of storage saved in the storage, which is variable and depends on the amount of consumption and production; and the `StorageEfficiency` represent the storage efficiency.

3.3.2 With Feed-in-Tariff With limitation to Sell

In this scenario it is considered a limitation on the amount of the electricity that can be sold by the house owners. This limitation is defined as a percentage of the production in each hour. The `LimitationToSell` represent this percentage. The main strategy to calculate the cost is similar to the Algorithm 3, with this difference that the maximum amount is considered for selling to the grid is `LimitationToSell` percentage of the production in each hour. The strategy to calculate the cost is presented in the Algorithm 4.

3.3.3 With Net-Metering

In this scenario, which includes energy storage, it is needed to separate the off-peak and on-peak periods. During the off-peak period, the energy generated should be stored in the battery to be used in on-peak period, so that the energy needed for the house can be simply bought from the grid. In the case the energy generated totally charges the storage, the remained one can be sold to the grid. In contrast, during the on-peak period, the electricity needed for the house is supplied first by the energy generated if any, second by the storage, then if the consumption is even more that the stored electricity, it must be bought from the grid. It is presented in the Algorithm 5.

Algorithm 3 Algorithm for Calculating the Cost in An Energy House With a PV and Storage System with Limited Capacity

```
Require: Consumption
Require: Production
Require: Price(B)
Require: Price(S)
Require: Cost
Require: StorageCapacity
Require: StoredEnergy
Require: StorageEfficiency
  if $Consumption \leq Production$ then
  ▷ Uses the amount needed from the production
      $Surplus \leftarrow Production - Consumption$
  ▷ Saves the surplus electricity produced as mush as remained capacity in the storage
      $StorageRemainedCapacity \leftarrow StorageCapacity - StoredEnergy$
      if $StorageRemainedCapacity \geq surplus$ then
          $StoredEnergy = StoredEnergy + Surplus$
      else
  ▷ Sells the remaied electricity produced
          $StoredEnergy \leftarrow StorageCapacity$
          $Surplus \leftarrow Surplus - StorageRemainedCapacity$
          $Cost \leftarrow -1 * Surplus * Price(S)$
      end if
  else
  ▷ Uses from the electricity produced
      $Consumption \leftarrow Consumption - Production$
  ▷ Then uses the storage if it has enough and also the price to buy is greater than the price to sell
      if $Price(B) \geq price(S)$ then
          if $StoredEnergy * StorageEfficiency \geq Consumption$ then
              $StoredEnergy \leftarrow StoredEnergy - Consumption/StorageEfficiency$
          else
  ▷ Buys the rest from the grid
              $Consumption \leftarrow Consumption - StoredEnergy * StorageEfficiency$
              $StoredEnergy \leftarrow 0$
              $Cost \leftarrow Consumption * Price(B)$
          end if
      else
  ▷ Buys all the electricity from the grid and doesn't use the storage $Cost \leftarrow Consumption * Price(B)$
      end if
  end if
```

Algorithm 4 Algorithm for Calculating the Cost in An Energy House With a PV and Storage System with Limitation for Sell

```
Require: Consumption
Require: Production
Require: Price(B)
Require: Price(S)
Require: Cost
Require: StorageCapacity
Require: StoredEnergy
Require: StorageEfficiency
Require: LimitationToSell
  if $Consumption \leq Production$ then
  ▷ Uses the amount needed from the production
    $SurplusProduction \leftarrow Production - Consumption$
  ▷ Saves the remained electricity in the storage
    $StorageRemainedCapacity \leftarrow StorageCapacity - StoredEnergy$
    if $StorageRemainedCapacity \geq SurplusProduction$ then
      $StoredEnergy = StoredEnergy + SurplusProduction$
    else
  ▷ Sells the remaied electricity produced
      $StoredEnergy \leftarrow StorageCapacity$
      $RemainedProduction \leftarrow RemainedProduction - StorageRemainedCapacity$
      $Cost \leftarrow -1 * Min(RemainedProduction, LimitationToSell * Production) * Price(S)$
    end if
  else
  ▷ Uses from the electricity produced
    $RemainedConsumption \leftarrow Consumption - Production$
  ▷ Then uses the storage if it has enough and also the price to buy is greater than the price to sell
    if $Price(B) \geq price(S)$ then
      if $StoredEnergy * StorageEfficiency \geq Consumption$ then
        $StoredEnergy \leftarrow StorageSize - RemainedConsumption / StorageEfficiency$
      else
  ▷ Buys the rest from the grid
        $RemainedConsumption \leftarrow RemainedConsumption - StoredEnergy * StorageEfficiency$
        $StoredEnergy \leftarrow 0$
        $Cost \leftarrow RemainedConsumption * Price(B)$
      end if
    else
  ▷ Buys all the electricity from the grid and doesn't use the storage $Cost \leftarrow RemainedConsumption * Price(B)$
    end if
  end if
```

Algorithm 5 Algorithm for Calculating the Cost in An Energy House With a PV and Storage System with Limited Capacity Using net-metering

```
Require: Consumption
Require: Production
Require: Price
Require: StorageCapacity
Require: StoredEnergy
Require: Off_Peak_Period
Require: On_Peak_Period
Require: Cost
Require: StorageEfficiency
  if $current_hourinOff\_Peak\_Period$ then    ▷ It has to save the production and buys from the grid if needed
      $StorageRemainedCapacity \leftarrow StorageCapacity - StorageSize$
      if $Production > StorageRemainedCapacity$ then
          $StoredEnergy \leftarrow StorageCapacity$
          $RemainedProduction \leftarrow Production - StorageRemainedCapacity$
          if $RemainedProduction >= Consumption$ then
              $Cost \leftarrow -1 * (RemainedProduction - Consumption) * Price$
          else
              $Cost \leftarrow (Consumption - RemainedProduction) * Price$
          end if
      else
          $StoredEnergy \leftarrow StorageSize + Production$
          $Cost \leftarrow Consumption * Price$
      end if

  else    ▷ It has to use the production if needed and save the rest until the last hour in the HighPriceDomain, and sell what is stored in that the last hour
      if $Production \geq Consumption$ then
          $RemainedProduction \leftarrow Production - Consumption$
          $StorageRemainedCapacity \leftarrow StorageCapacity - StoredEnergy$
          if $RemainedProduction > StorageRemainedCapacity$ then
              $StoredEnergy \leftarrow StorageCapacity$
              $RemainedProduction \leftarrow RemainedProduction - StorageRemainedCapacity$
              $Cost \leftarrow -1 * RemainedProduction * Price$
          else
              $StoredEnergy \leftarrow StorageSize + RemainedProduction$
          end if
      else
          $RemainedConsumption \leftarrow Consumption - Production$
          if $RemainedConsumption > StoredEnergy * StorageEfficiency$ then
              $Cost \leftarrow (RemainedConsumption - StoredEnergy * StorageEfficiency) * Price$
              $StoredEnergy \leftarrow 0$
          else
              $StoredEnergy = StoredEnergy - RemainedConsumption / StorageEfficiency$
          end if
      end if
  end if
```

Chapter 4

Evaluation and Analysis

The main purpose in this chapter is to assess how the maximum possible benefit could be achieved out of an nearly-zero energy house by considering the existing tariff rates including net-metering and feed-in-tariff (FIT). Also the effect of storage size on benefit is studied. In this chapter the specifications of the nearly-zero energy house, including the energy consumption and generation are first presented, followed by the results.

4.1 Specifications of the Nearly-Zero Energy House

The nearly-zero energy house considered for the analysis is placed in Coimbra, Portugal. This house is equipped with photovoltatic systems and storage system. This storage system could be a lithium-ion battery, which is the best kind of batteries to use in a residential place because of its high efficiency and long lifetime.

The consumption profiles of the house were recorded by a monitoring system, which had been installed in the house during one year. The information were available in the Energy for Sustanability research group of the University of Coimbra. The house in this work is not equipped with photovoltaic panels in reality, so that a PV system is assumed in this analysis. The generation profile of this PV system is provided by PVWatts [55]. The PVWatts is a simulator developed by the National Renewable Energy Laboratory (NREL), to design and evaluation of solar PV systems.

This application allows users to select a size and location for a PV system. In this work, the size of the integrated PV system considered into the house is $4kW$ which is the maximum PV system size regarding the 6.9 kW contracted power. The size of a PV system is its nameplate DC power rating. PV module power ratings are for standard test conditions (STC) of 1000 W/m^2 solar irradiance and $25°C$ PV module temperature. This size corresponds to a PV array area of approximately $35m^2$ $(377ft^2)$ of crystalline silicon, but this number can be different for each kind of solar panels because of technology advance and increasing the efficiency. The PVWatts system uses hourly typical meteorological year (TMY) weather data and a PV performance model to estimate annual energy production for a PV system. DC-to-AC Derate Factor is another important parameter to create the energy generation profile using PVWatts. PVWatts multiplies the nameplate DC power rating by an overall DC to AC derate factor to determine the AC power rating at standard test conditions (STC) [56]. A list of the default component derate factors used by PVWatts and the ranges that might be encountered in practice are listed in Table 4.1.

Table 4.1: Derate Factors for AC Power Rating at STC

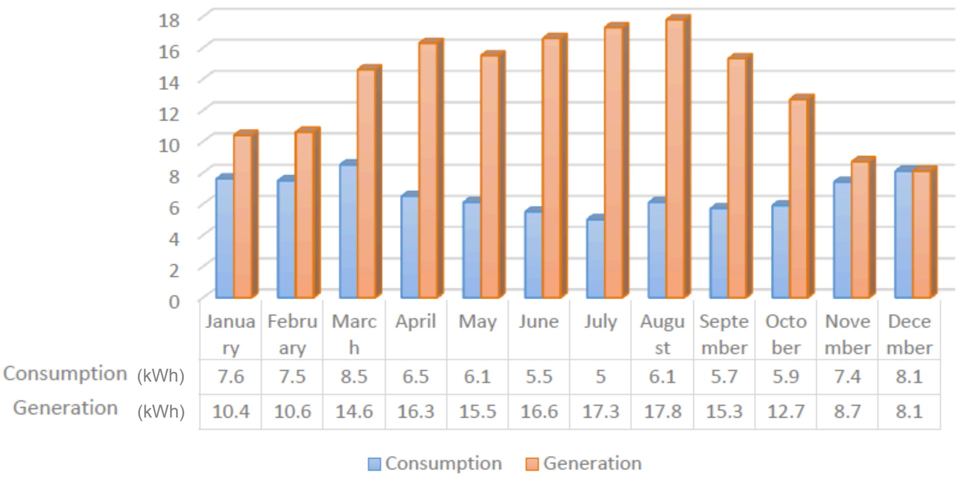
Component Derate Factors	PVWATTS Default	Range
PV module nameplate DC rating	0.95	0.80-1.05
Inverter and transformer	0.92	0.88-0.98
Mismatch	0.98	0.97-0.99
Diodes and connections	0.995	0.99-0.997
DC wiring	0.98	0.97-0.99
AC wiring	0.99	0.98-0.993
Soiling	0.95	0.30-0.995
System availability	0.98	0.00-0.995
Shading	1	0.00-1.00
Sun-tracking	1	0.95-1.00
Age	1	0.70-1.00
Overall DC to AC derate factor	0.77	

The overall DC to AC derate factor is calculated by multiplying the component derate factors as it is shown in equation 4.1. The value of 0.77 means that the AC power rating at STC is 77 % of the nameplate DC power rating.

$$\texttt{Overall DC to AC Derate Factor} = \tag{4.1}$$

$$0.95 \times 0.92 \times 0.98 \times 0.995 \times 0.98 \times 0.99 \times 0.95 \times 0.98 \times 1.00 \times 1.00 \times 1.00 = 0.77$$

Figure 4.1 shows the daily consumption and generation average for a year. Obviously, the amount of consumption is higher in winter. Heating system and hot water systems are the main reasons for that. The amount of energy generated by PV system is lower in winter as it is supposed to be. According to the data shown in the figure 4.1, electricity generated through this PV system is much more than the consumption with the daily average of 13 kWh (7 kWh consumption average), only in winter the difference is not very high especially in December, which is almost equal.



	January	February	March	April	May	June	July	August	September	October	November	December
Consumption (kWh)	7.6	7.5	8.5	6.5	6.1	5.5	5	6.1	5.7	5.9	7.4	8.1
Generation (kWh)	10.4	10.6	14.6	16.3	15.5	16.6	17.3	17.8	15.3	12.7	8.7	8.1

FIGURE 4.1: Daily Consumption and Generation Average

Figure 4.2 shows the hourly average of the consumption and generation which means the average of the consumption and generation in a certain hour during the year. In spite of the fact the PV system only generates electricity in presence of the sun and has a limited generation period, the overal amount of the generation is higher than consumption in a year.

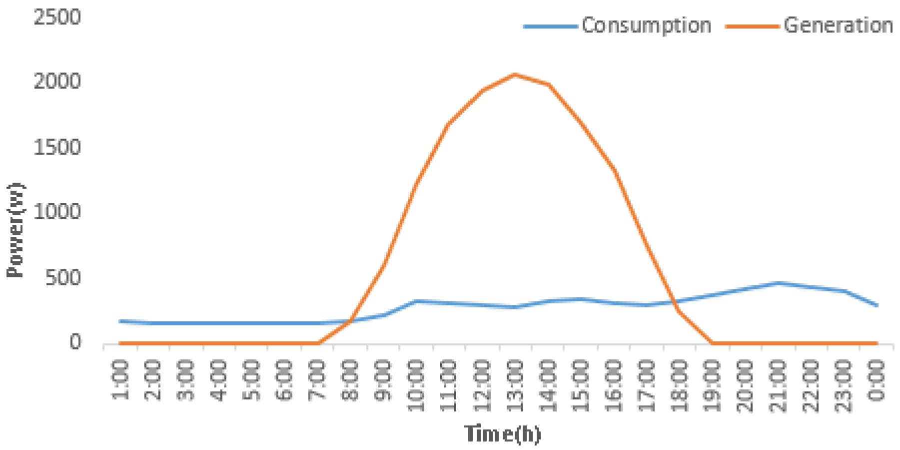


Figure 4.2: Hourly Consumption and Generation Average

4.2 Cost Analysis

According to the Portugal electricity pricing policy, the consumers can select between a flat tariff and tariffs with 2 or 3 time periods. In a tariff with different time periods, the consumer must select a daily or a weekly cycle. In this work, the tariff with 2 time periods (On-Peak and Off-Peak) in a daily cycle which is most common, is considered. Table 4.2 shows the different tariffs defined by EDP company [54] in Portugal.

Table 4.2: Electricity Tariff Defined by EDP in Portugal

	Period	Electricity Price ($Euros/kWh$)
Flat Tariff	Single Period	0.1528
Tariff with 2 Periods	On-Peak	0.1785
	Off-Peak	0.0946
Tariff with 3 Periods	On-Peak	0.2029
	Mid-Peak	0.1613
	Off-Peak	0.0946

Regarding Table 4.2, in daily period there are two different electricity prices for each period (On-Peak, Off-Peak): 0.1785 €/kWh for On-Peak period, which starts from 8 AM and finishes at 22 PM and 0.0946 €/kWh for Off-peak period which is charged for the rest of the hours. Two policies are considered to accomplish this analysis: feed-in-tariff and net-metering. At the present time the feed-in-tariff that portuguese utility is obliged to pay for photovoltaic renewable energy is 0.13 €/kWh for first 8 years and 0.02 €/kWh for rest of operation years until 15 years.

In contrast to the feed-in-tariff system there is net-metering system. A bidirectional meter is used in this system, which rotates backwards when the energy generated exceeds its own consumption. In this way, only the net energy exchanged is measured at the point of connection, if the generation is greater than the load the consumer receives a credit either in energy or cash for the next bill. Otherwise, the customer will pay only the difference between the energy consumed and the energy produced. In this system the price to buy and sell the energy are usually equal but according to new regulation in Portugal the price to sell in net-metering policy system is 10% les than the market price.

4.2.1 Effect of PV System on Cost

Making benefit out of PV systems is the obvious goal of using them in residential or non-residential buildings. In this section the amount of benefit gained using PV system in the residential building is calculated. For this purpose, first the cost is calculated without a PV system and then the benefit gained is calculated after using a PV system. Figure 4.3 shows the differences between two cases in one year, one with PV system and another without it. As it is shown in the figure 4.3, PV system, apart from the its installation and initial cost, makes huge difference for such building, although it is just an residential one in terms of size. The amount of the benefit is higher in the summer, obviously due to climate situation.

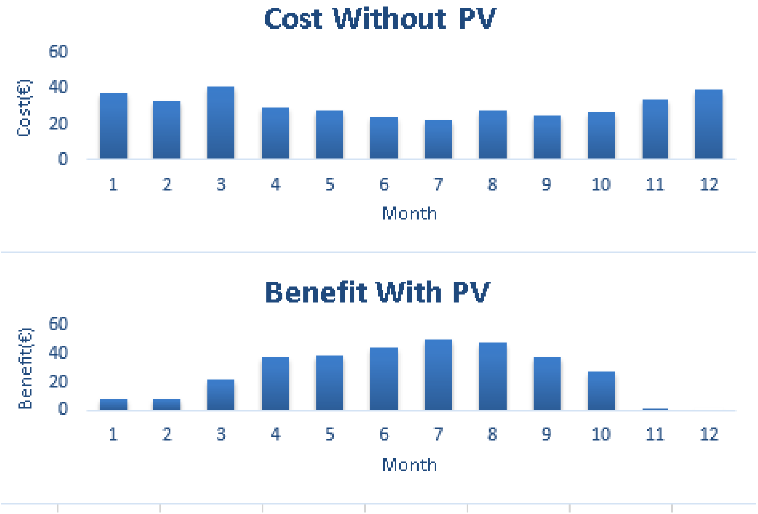


FIGURE 4.3: Difference between cost and benefit with PV and without PV system

Disregarding to the PV system and its generation, the building consumed 2450 kWh of electricity and must pay 395 Euro in one year, while installed PV system generates about 4900 kWh in one year. Without self-consumption (which means all electricity generated is sold to grid directly) the owner will earn 650 Euro by selling the electricity and the net benefit in this way is 255 Euro. However, by considering self-consumption the owner benefits 320 Euro (of course without considering the installation cost). This value is significantly high and reduces the role of management in consumption and generation. But the important point is that the FIT is reducing every year, so that it will be more profitable for the owners to save the electricity produced instead of selling them. For instance after first 8 years, with 0.13 euro/kWh FIT, it reduces to 0.02 euro/kWh until year 15, with this new FIT in the second period, the owner does not earn any money and should pay 115 Euro for the electricity for a year.

In the second step of the analysis, the benefit is calculated for the house with net-metering system. This analysis is done to show the differences between two systems (FIT and Net-metering). In net-metering system the price to sell and to buy are the same (refer to Chapter 3) but according to the new regulation in Portugal the price for selling the electricity is 10% less than market electricity price which was 0.039 euro/kWh in 2013. Figure 4.4 shows the results. The main observation is that the benefit gained with Portugal's current actual FIT is higher than the benefit in a net-metering system in all months of a year. Base on the calculation the owner should pay 73 Euro for the electricity for one year. With using the net-metering policy system there is no benefit, only the cost for electricity which owner has to pay reduces from 395 Euro to 73 Euro.

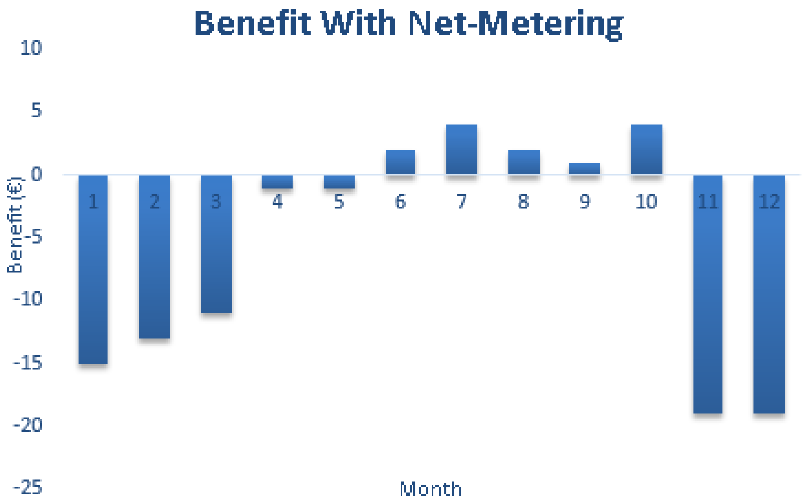


FIGURE 4.4: Benefit gained with PV system using Net-Metering policy

It should be mentioned again that in Net-Metering system the excess power sent to the grid is not paid in every country, but the generator unit receive a credit for the next months.

4.2.2 Effect of Storage System and Its Size on Benefit

In this section the benefit gained is calculated by using storage in the building and the result is shown in comparison with a building without an energy storage.

4.2.2.1 Using Feed-In-Tariff

Before presenting the effect of using storage system on cost, figure 4.5 presents the load diagram of the house. It should be mentioned that figure 4.5 present the load diagram while the storage system size is 5 kWh and FIT is 0.13 euro/kWh. During the peak generation the surplus generated electricity is stored in battery and later at night is consumed and when the battery charged completely the rest of electricity is sold to grid.

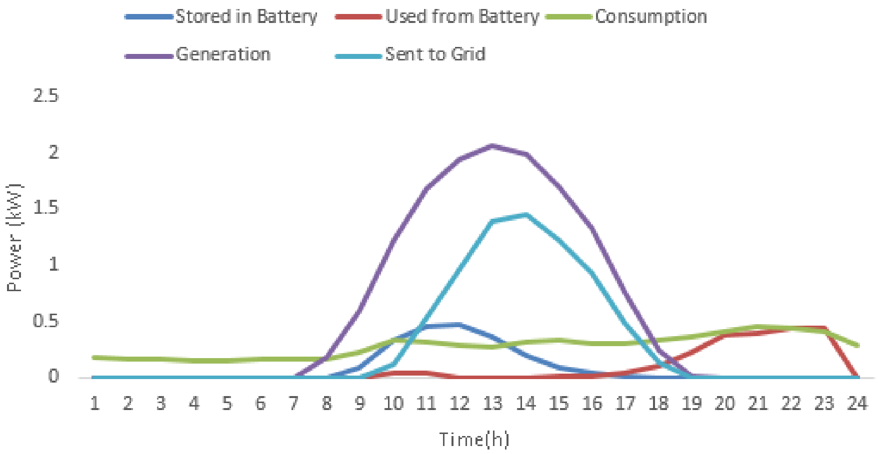


FIGURE 4.5: Load Diagram Of The House

Figure 4.6 shows the comparison between the situation without using battery and considering batteries with different sizes(from the minimum possible size to the highest reasonable size for a house: 1 kWh, 5 kWh and 10 kWh). Since, the generation level is much higher than the consumption in the periods of higher consumption costs, self-consumption is the most profitable option and storing the electricity is not reasonable. Not only using storage system does not makes more benefits but also it even reduces the benefit. However, the difference is not significant. It still does not seem reasonable to use energy storage in the houses by considering the extra expenses that is needed to buy the battery and install it. It is not still an efficient solution with current tariffs. Because with the current FIT, most benefit will gain when the surplus electricity is sold to grid and the storage makes lower benefit because of the energy loss during the charge and discharge and for this reason smallest size of storage in better than other (1 kWh in this study).

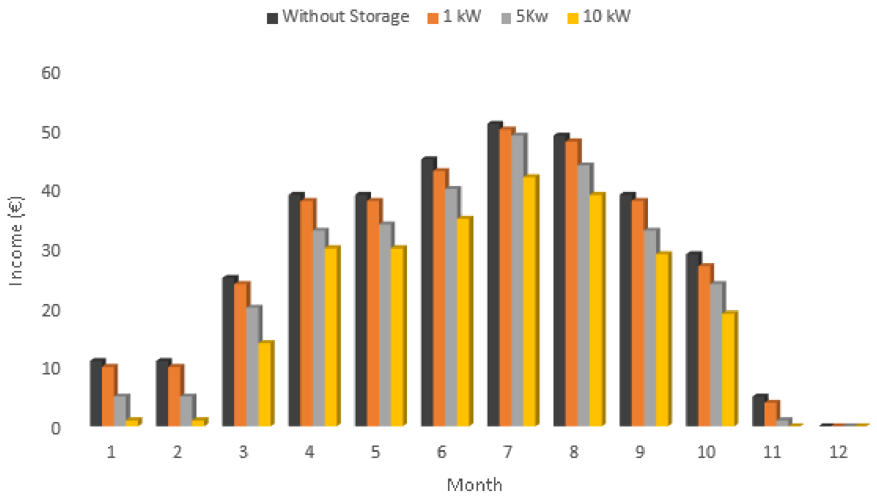


FIGURE 4.6: Cost-Benefit Comparison without Storage and with Storage using FITs

The storage system will be more effective when FIT is lower than the present value, for this reason a same comparison was done when the FIT is 0.02 Euro/kWh (After 8 years). According to the new results, storage system makes a huge difference in the cost and should be mentioned that in this stage the battery with 5 kWh size has the best result. The owner must pay 115 euro for the electricity in one year (395 euro without PV) with new FIT (0.02 euro/kWh), while this value decreases to 37 euro using the storage system. It should be mentioned that in the second period (from year 8 to 15) the owner does not earn any money from this system with the new price and the storage system only reduces the cost.

The above analysis are done without assuming any limitations on the amount of the electricity might be sold to the grid. Thus, two different percentages of the generation which can be sold (i.e. 50%, and 75%) were used and it is compared with the case without limitation. The Figure 4.7 shows the results.

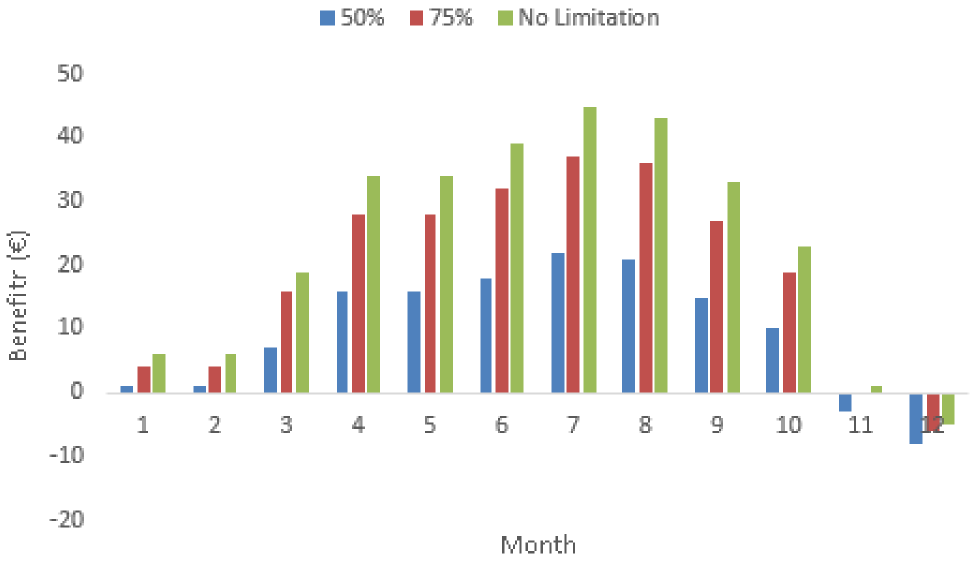


Figure 4.7: Cost analysis considering limitation on sell

It is clear that the benefit will be lower when the limitation to sell is more, for instance as figure 4.7 shows, benefit is lower when only 50% of the generated electricity is allowed to sell.

According to the present value of FIT in Portugal, the maximum benefit made by this system with storage and no limitation is 313 Euro in one year and after the 8 years it will be 2504 Euro, which is 50% of the initial cost of the storage system with size of 5 kWh. Different batteries have their characteristics, among them lithium-ion is the proper device for this application because of its high efficiency and long life cycle of 3000 (8 years) cycles. This battery costs approximately 5000 Euro, but this value is decreasing every year.

4.2.2.2 Using Net-Metering

Using the net-metering policy system makes lower benefit than FIT policy in all scenarios. However, the impact of the storage system on benefit is significant with current price. In the current situation which the selling price is low, the storage system is effective to benefit more. The owner earns 25 euro in net-metering policy in one year with using the storage system while without storage he earn nothing.

Chapter 5

Conclusion And Future Work

Since using PV and energy storage system are becoming common in the buildings and specially in residential houses, in this research work the cost of a grid connected house in different scenarios is assessed: without PV system, with PV system, and with both PV and storage systems. To explore the assessment, several sizes for the energy storage were considered to verify the effect of its capacity on the cost. Moreover, two different supporting policies including feed-in-tariff and net-metering are considered to observe the impact of different policies on the cost.

Through the simulation of the nearly-zero energy house, it was concluded that not only the price, which each supporting policy present is a very important element for the benefit or cost but also the restrictions (mandatory self-consumption) is important as well. Moreover, energy storage size also plays a important role. Table 5.1 shows an overview of the result.

TABLE 5.1: Cost or Benefit In Different Scenarios For One Year

Scenarios	Cost(Euro)	Benefit(Euro)
Without PV	395	
FIT(0.13)		320
FIT(0.13) with Storage		313
FIT (0.02)	115	
FIT(0.02) with storage	37	
Net-Metering	73	
Net-Metering with Storage		25

As discussed before, actually there is no economic reason for consumer to use the storage system, mostly because of the actual energy tariffs offered by utilities. This assessment was done to the maximum level of PV power which is the most typical situation in the Portuguese households. However, in household with the same level of generation and consumption the role of energy storage can be much more important, since it is possible to achieve a matching between the generation and consumption. In such situations the economic benefits ensured by energy storage is also higher.

However, in a near future, the tariffs to consumption and generation will vary in a near real-time basis and due to the decrease on the tariffs, the self-consumption of the generated energy could be the most advantageous option. In such situations, using storage system for optimization between the energy consumption and generation, presented in this thesis, will be very important to ensure smaller environmental impacts, higher system reliability and lower costs. In future there will be significant development in reducing the battery cost and improving their efficiency duo to their massive application in electric vehicles and building. According to some research and investment the cost of batteries is decreasing 15% in every year and this development will help the storage system to be more economical for small scale applications.

As an interesting future trend of this work is to obtain conclusions from the observations of the assessments to improve the scheduling algorithms running on the storage. The main goal for improvement of the scheduling algorithm would be to take the most benefits from the technologies included in such nearly-zero energy house to decrease the overall cost in long term. The same assessment can be done for a building with different sizes, different consumption and generation levels and for a group of the building in a neighborhood as well.

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