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Energy Storage in Electric Power Generation Plant from Renewable Sources

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Abstract

During last years the utilization of renewable energy resources has received considerable attention because of the adverse environmental impacts and cost escalation of conventional fuel generation plants. Solar photovoltaic and wind energy industries are two sectors very rapidly growing, and both of them are attracting investments of billions of dollars. However, photovoltaic and wind, like most of the renewable energy sources are characterized by high variability and discontinuity. The high unpredictability of the primary resource makes difficult to forecast the energy production. This is a major trouble for network utility grid management and for the final user, especially in the case of systems operated in island mode. Application of high efficiency energy storage techniques could stimulate in a near future a larger exploitation of renewable energy sources. Energy storage, in fact, could not only improve the quality of the produced power, but, it could also make possible the implementation of sophisticated energy management strategies, fully decoupling the power delivery from power generation.

Acknowledgments

This work has been done in collaboration with the Scuola superiore of catania and Isab Energy of Priolo Gargallo – Siracusa. Acknowledgements are given to afore mentioned institutions for their financial support.

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Chapter 1

Introduction

1.1 Introduction

The availability of fossil fuels has had a crucial role in the development of the modern civilization in the last two centuries. However, the raise of primary energy request caused by the demographic growth in developing countries and by an energy starving style of life in developed countries, will lead to an unsustainable situation in the near future, due to the limited fossil fuel reserves still available. From the oil crisis of the early 70s to date, the progressive exhaustion of the traditional energy sources had become, a major awareness. Therefore, studies and researches oriented to a broader exploitation of renewable energy sources are powered, as a response to difficulties today experienced in industrialized countries in primary energy procurement. Moreover, renewable energy sources represent a quite viable solution to the worrisome increase of air pollution, because of their zero or very low emissions. Among renewable energy technologies, those of photovoltaic cells and wind turbines are indeed the most popular, both featuring no pollution and being advantaged by a large availability of an inexpensive primary energy. In the past, their diffusion was limited by technological shortcomings and higher costs if compared with traditional generation techniques. However, thanks to the technological progresses of the last two decades the efficiency and reliability of photovoltaic and wind generators have been improved while the costs have been noticeably lowered. Although a full commercial competitiveness with conventional systems today is not still reached, potential benefits of large scale production and the constant raise of the cost of fossil fuels could result in an acceptable level of competitiveness in a short time.

As can be seen in Figure 1.1, a rapidly growing use of renewable sources (mainly wind) is today experienced. Furthermore, until 2004, nearly 50% of energy world-wide obtained from renewable sources has been produced in Japan, which is still the world leader in manufacturing and installation of photovoltaic systems. The country that has most encouraged the exploitation of renewable energies in Europe, is Germany, although Spain and Denmark are remarkably recovering. In these countries noticeable changes were made to traditional electric energy generation and management strategies, also exploiting conventional and innovative storage technologies. According to the forecasts of the European Union the incidence of the renewable sources on the whole continental electric energy production should reach a 20% within the 2020. In some regions, more suitable where will be able to overcome even the 50%.

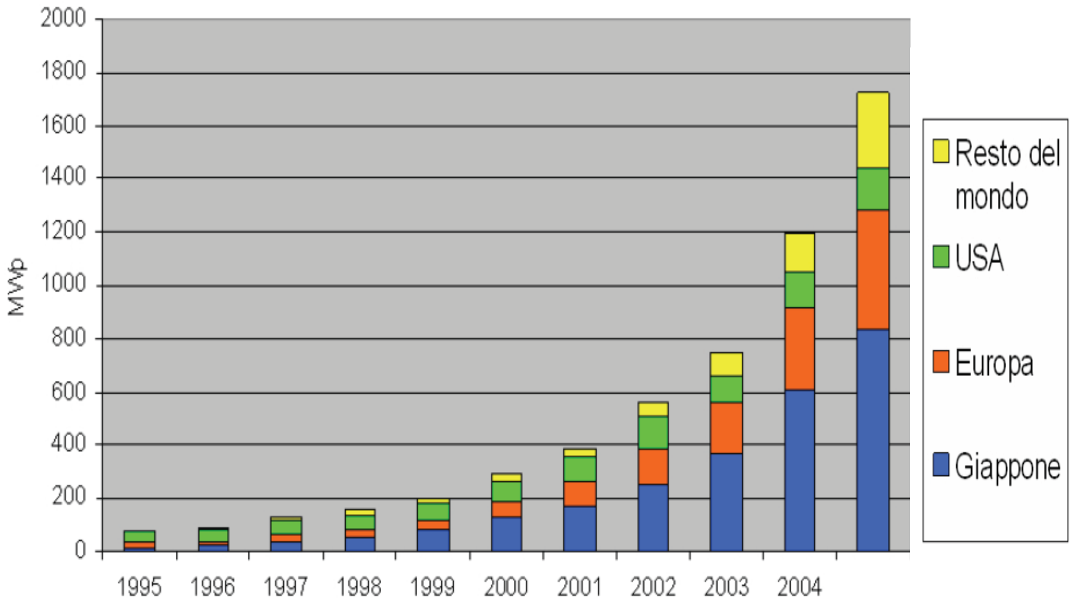


Figure 1.1 - Impact of the renewable in the world

Figure 1.2 shows the worldwide projected increase of energy production from renewable sources. In the view of growing public support and government incentives ,in the future years an increase in rated power installed from renewable sources installed higher than estimated expectations can be expected.

In Italy, thanks to the significant contribution of government incentives, some renewable sources reached very encouraging developments. The new photovoltaic capacity installed in only 2009 (574 MWp) was far higher than total quantity installed until the previous year (458 MWp), exceeding the threshold of 1 GWP. For wind energy, Italy is the third country in Europe in 2009, both for new installed capacity (1,113 MW) that for total installed power (4850 MW).

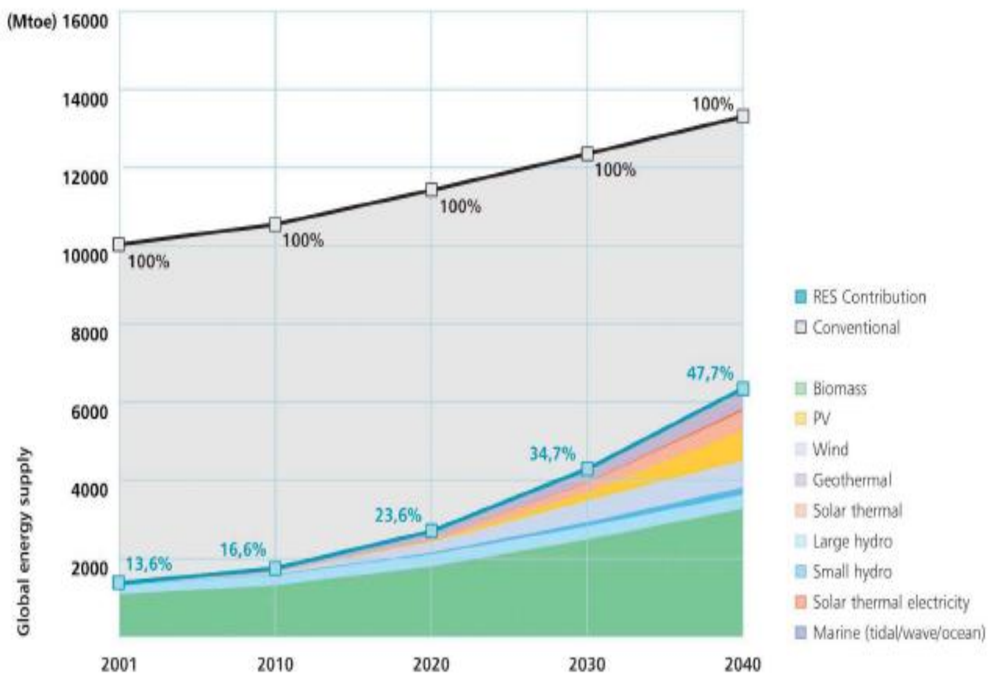


Figure 1.2 - Estimated growth of energy production from renewable sources in the world

The effective power availability from a renewable energy source depends on the variation of the primary resource over the time, which show seasonal, daily or instantaneous dynamics. The wind undoubtedly is the renewable energy source that more than the others suffers from the variability. As shown in Figure 1.3, it is generally impossible to determine exactly the daily production of a wind farm. In particular it can be seen that variations of the wind speed, results in noticeable fluctuations of the output power. Photovoltaic plants are also heavily influenced by weather conditions, moreover, they feature a limited period of operation over the day. The non fossil source that show the lower variability is the geothermal energy, whose exploitation is however possible only in few areas.

Because of the unpredictable availability of power photovoltaic panels and wind turbines cannot ensure the minimum level of power continuity required to supply a generic network of electrical loads. Therefore, they must be integrated with energy storage devices and/or auxiliary generators, in order to decouple the energy generation from the delivery [1].

Moreover, a distinction must be made between "island" mode of operation, where the generator operates disconnected from the main network and "grid connected" mode of operation, where the generator is permanently connected to the main network. In fact, while in the last case the stability is theoretically guaranteed by the power prevalence of the main network, particularly critical is the first operation mode, as a suitable accumulation system is mandatory to balance the differences between the available primary power and the requested load power.

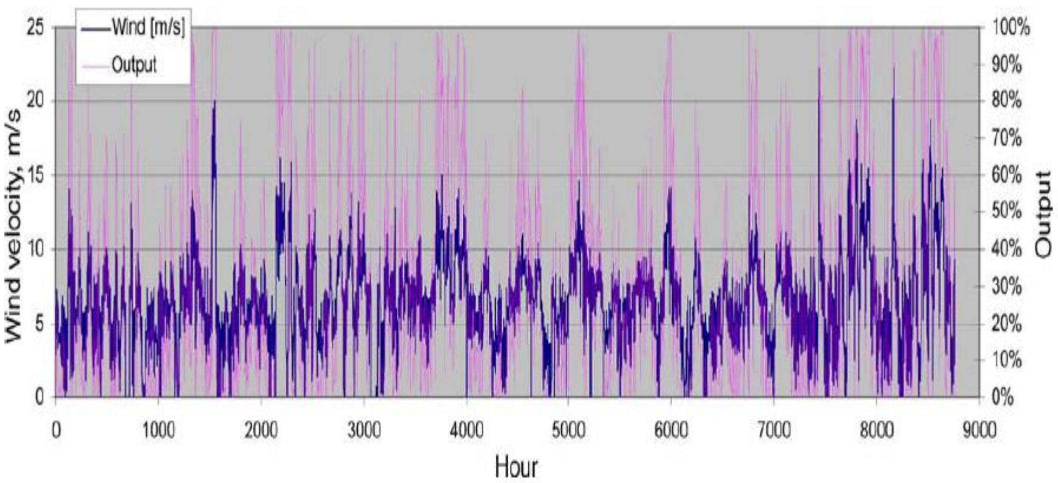


Figure 1.3 - Percentage course of the power in exit from a wind turbine

The stability of the Italian national network is ensured by interaction between a core of fossil fuel (natural gas, oil and coal) generation plants, providing the base power, and a set of peak power generation plants (hydro and gas turbine) distributed throughout the country, supporting rapid load changes. In the rest of the Europe the scenery is different for the presence in some countries of nuclear power stations, that, on one hand guarantee a substantial portion of the basic power but, on the other hand, require complex energy management strategies. Traditional electric systems are however not able to support the expected rapid proliferation of renewable energy generation plants, at least without introducing new management strategies and accumulation plants. In fact, the power generated by wind farms today is limited to 15% of the total power distributed through the network in order to ensure stability. This claims for the introduction of suitable accumulation systems in association with the activation of further generation plants from renewable sources.

In the perspective of a broad use of renewable energy generators and therefore of a proliferation of large size accumulation systems, cost, reliability and durability of these systems could significantly affect the economy and reliability of national electricity system.

1.2 Objectives and motivations

The optimal sizing of energy storage systems for generation plants from renewable sources is an extremely complex task, that requires an interdisciplinary knowledge and suitable computation and simulation tools. Moreover, standard rules have not be defined and universally accepted until now. Therefore, the design is mainly performed case by case, exploiting the available know-how and the accessible technologies.

The main objective of the work is to develop general design rules for the accumulation system, accounting for the specific features of the renewable energy source generation system, the grid connection and the load time diagram.

In order to develop such rules it is first necessary to build a suitable mathematical model of the system and to identify mathematical relationships describing the interaction among the different elements of the system, the interaction between the system and the primary energy source and the interaction between the system and the grid.

This lead to analyse:

- on the availability and variability of the different renewable energy sources;
- on energetic and dynamical features of generation systems;
- on output power, energy, and response features of accumulation systems;
- on typical load diagrams of the considered applications;
- on control and management strategies of the generation and accumulation systems;

- on the environmental impact, especially in terms of required space and use of potentially dangerous materials.

1.3 Main Activities

In the first year of my PhD course main attention was focused on the acquisition of a basic theoretical knowledge of energy transformation, energy conversion and energy storage. During this year, I attended three academic courses and several seminaries concerning different topics in the area of the energy.

In this first year my research activity has been primarily focused on some aspects of the distributed generation. Distributed generation systems can offer increased reliability, uninterrupted service while lowering energy costs. Different electric power generators, such as: Fuel-cells, microturbines, wind turbines, or photo-voltaic cell arrays are today considered to be introduced in distributed systems. These devices generate a DC voltage that must be converted into an AC voltage, suitable for residential or industrial use through DC/AC converters (inverters). A key feature of conventional inverters is that the peak AC output voltage is always lower than the input DC voltage. Therefore, when a peak AC output voltage larger than the DC input voltage is required, a further DC-DC boost converter must be inserted between the voltage source and the inverter.

At the end of the first year, a two years long research project was defined with Dr. Iannitti of the ERG firm and Prof. Testa to study storage devices aimed to equip generation systems from renewable energy sources. This project, called "*Energy Storage in Generation Systems from Renewable Sources*" started from an evaluation of the energy storage technologies scenario and possible applications of available devices. The discontinuity of renewable energy sources and the problems related to the sizing of storage system have been then accounted. A special emphasis was placed on VRB-ESS and Electrolyzer + Fuel cell systems.

In the second year of my PhD course the attention was focused on the development of design tools to accomplish an optimal sizing of hybrid generation systems including energy storage devices.

Available energy storage devices differ in terms of specific power, energy capability, cost and maturity. Therefore, the design of energy storage systems is a complex task, which requires an interdisciplinary knowledge and suitable computation and simulation tools. The complexity of the task is also increased by the possibility to combine together different technologies in order to satisfy the specifications in terms of power density, storage capability and cost.

The first step to accomplish along the design of an energy storage device is to evaluate the effects of input power variations on the loads through accurate models. Suitable mathematical tools, able to analyse the dynamic behaviour of generation systems and storage devices, are then required to determine the storage technology and the storage capacity that best fit the load requirements. The development of these tools has been the objective of the second year activity that will be reported in the following sections, together with a brief overview of two papers presented at the EPE 2009 Conference held in Barcelona Spain in September 2009.

Another project was started in co-operation with CNR-ITAE of Messina. The aim of this work was a comparative evaluation of some regenerative energy storage technologies, specifically VRB-ESS and Fuel Cell + Electrolyzer systems. The set of parameters to be compared includes: reliability, availability and the ability to perform maintenance work in a fast, effective and easy way.

In November 2009 I attended a course on Energy Management at LIUC University of Castellanza (VA). This course provided a comprehensive view of energy issues, with particular interest in the audit of the utilities and economic and productive assessments of renewable energies, especially photovoltaic. The kwon-how assumed during this course has been particularly useful for the activities of the third year.

In the third year of my PhD the attention was focused on grid connected generation systems exploiting renewable sources. The aim was the development of a general methodology to accomplish an optimal sizing of the power conversion system in PV plants either directly delivering power to the utility network, either equipped with energy storage systems. A new probabilistic approach has been developed starting from the basic L.P.S.P. index. The methodology is very simple and adaptable to different applications. Moreover the proposed approach provides a very interesting way to solve problems related to the discontinuous delivery of power to the utility network. This may result in frequent plant shutdowns, while requiring a remarkable reserve power to be provided by conventional generation systems. The proposed approach has been described in a paper presented at the ICEM 2010 Conference held in Rome, Italy, last September.

During the third year of my PhD a new co-operation with CNR ITAE regarding the sizing of stand-alone generation systems was also started. The aim of this co-operation was the realization of a software tool able to calculate the minimum size of the generation and storage system able to satisfy a given set of loads. This stand alone tool has been entirely realized in MATLAB. The software simulates the behavior of four types of storage systems (Vanadium Redox Batteries, Lead Acid Batteries , Li - ION, Fuel cell + Electrolyzer), considering some different renewable energy generation plants (solar, wind and hybrids). The accomplished analysis allows to estimate the initial cost of the system (considering the average costs of photovoltaic modules per m^2 and the average cost of wind turbines per kW) and the plant life cost. It is then possible to compare the cost of different configurations of the storage system in terms of kWh and kW. Two papers were published on this topic in co-operation with CNR ITAE, both presented at the SPEEDAM Conference held in Pisa, Italy, in June 2010.

In the context of the PhD course a further project was started in co-operation with Dr. Iannitti and Dr. Rabuazzo of Isab Energy. This project regards the application of electrochemical energy storage systems to a conventional Turbogas Generator (TG) in Priolo (SR). During daylight hours the plant has an almost constant operating rate, close to the point of maximum efficiency of the TG. On the contrary, overnight (from 10.00 pm to 7.00 am), the TG group needs to work at reduced power, leading to a reduction in efficiency as well as a lower gain. The aim of this work is the design of a suitable VRB energy storage system able to store all the surplus of energy produced during the night. This amount of energy is usually sold to the grid at very low price. Introducing an energy storage system this amount of energy can be stored during the night and then delivered during the day when the price of the energy on the market (MGP) is much higher

1.4 Scientific production

- "***Analysis of a VRB energy storage system for a tidal turbine generator"***
  A. Testa, S. De Caro, T. Scimone - European Conference on Power electronics and applications (EPE 2009), 8-10 September, Barcelona, Spain.

- ***"High efficiency field oriented control of an induction generator for a tidal current turbine"***
  A. Testa, S. De Caro, T. Scimone - European Conference on Power electronics and applications (EPE 2009), 8-10 September, Barcelona, Spain.

- ***"A solar AC module with active filter capabilities"***
  Testa, A.; Scimone, T.; De Caro, S.- International Symposium on Power Electronics Electrical Drives Automation and Motion (SPEEDAM 2010), 14-16 June, Pisa, Italy.

- ***"Optimal design of energy storage systems for stand-alone hybrid wind/PV generators"***
  A. Testa, S. De Caro, R. La Torre, T. Scimone - International Symposium on Power Electronics Electrical Drives Automation and Motion (SPEEDAM 2010), 14-16 June, Pisa, Italy.

- ***"Optimal size selection of Step-Up Transformers in PV Plants"***
  A. Testa, S. De Caro, R. La Torre, T. Scimone – International Conference on Electrical Machines (ICEM 2010), 6-8 September, Rome, Italy.

1.5 Attended Conferences

- EPE 2009 –"*European Conference on Power electronics and applications"*, 8-10 September, Barcelona, Spain.

- SPEEDAM 2010 –*"International Symposium on Power Electronics Electrical Drives Automation and Motion"* 14-16 June, Pisa, Italy.

- ISIE 2010 – *"International Symposium on Industrial Electronics"* 4-7 July ,Bari, Italy.

Chapter 2

Energy Storage System and Renewable Energy Sources

2.1 Classification of Energy storage technologies

The energy produced from a renewable energy source generation plant, both “in island mode” or “grid connected” can be stored as potential energy (chemical and/or mechanical) and then released when necessary. In Figure 2.1 main storage technologies today available are summarized. These technologies differ mainly in terms of capacity, storage time, cost and maturity [2],[3].

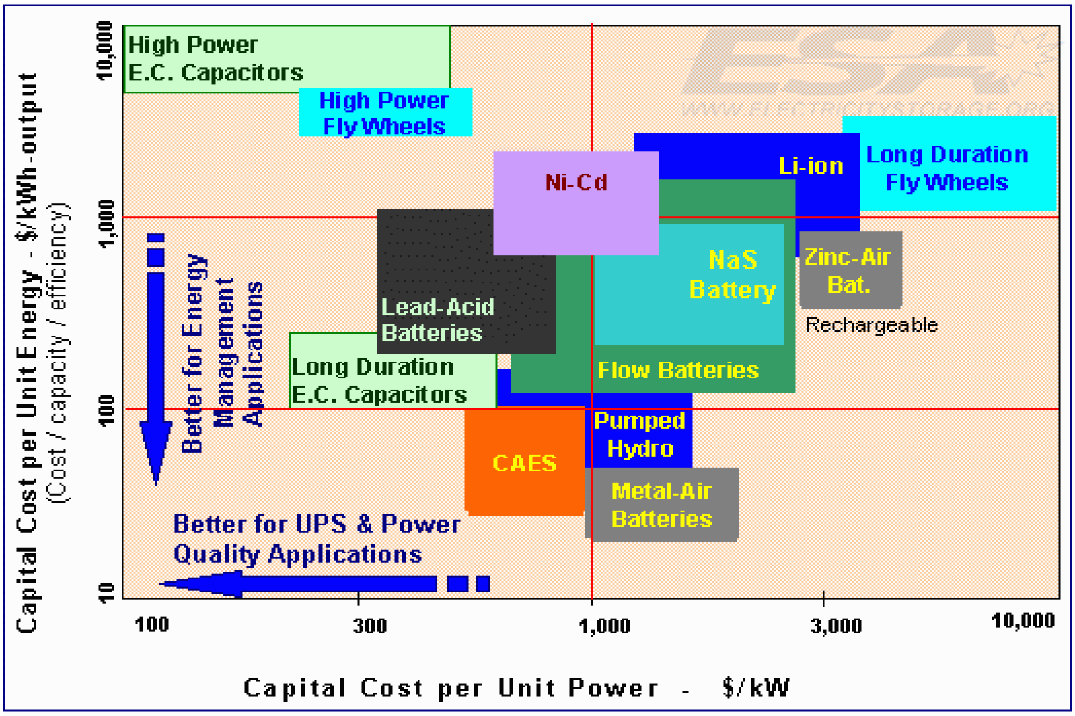


Figure 2.1 - Costs per unit of power produced/installed

A classification of various technologies in terms of power capabilities and storage capacity is also given in Figure 2.2. Based on these parameters the different storage technologies may fit the requirements of three different classes of applications:

- *Power quality - interactions with the grid for periods of the order of seconds*
- *Bridging power - interactions with the grid for periods of the order of minutes*
- *Energy management - decoupling production and delivery of energy*

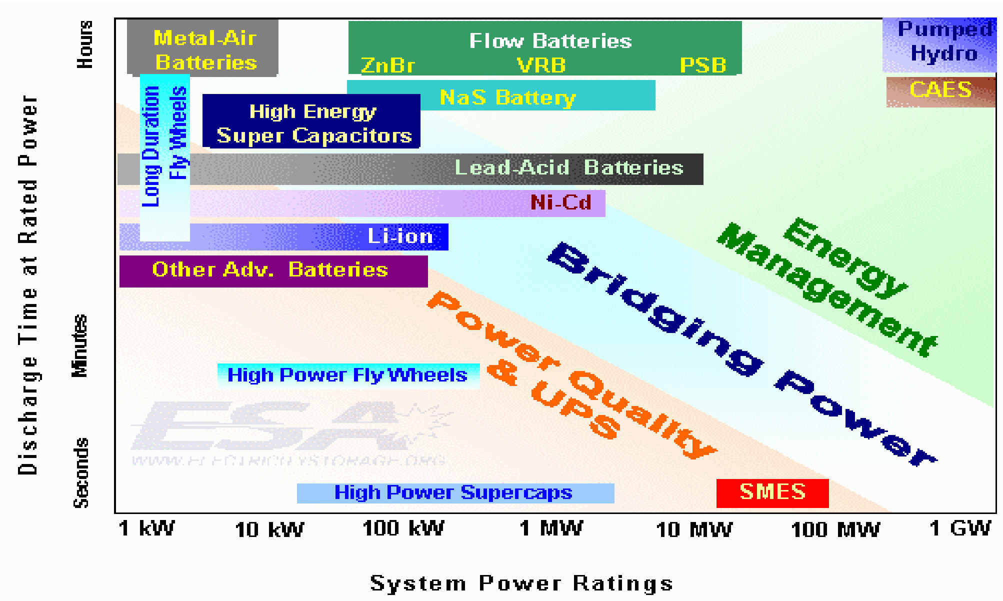


Figure 2.2 - Accumulation systems and they time of discharge in relationship of the power

An ideal accumulator owns the following main features:

- high storage efficiency;
- long operative life;
- high robustness to temperature variations;
- negligible self-discharge;
- high capacity/volume ratio;
- low cost;
- reduced maintenance

Key features of main available storage technologies are summarized in the following.

2.1.1 Hydroelectric storage system

The most traditional storage technique is that based on pumping water, from a tank to another placed at a higher level. The water is pumped from the lower tank to the upper tank when the produced energy is larger than the energy demand, and it is later used to produce electricity to face demand peaks. The upper tank may also store energy at zero cost by intercepting meteoric waters [4].

Hydroelectric systems are widespread used all over the world and their technology is very mature. They are able to quickly control the output power level in order to follow the variations of the load power demand. Furthermore, this technology produces no emissions.

However the density of accumulated power is poor, moreover the realization of new artificial basins an dams is more and more difficult, partially due to the worries of the public opinion after some disasters happened in the last years.

The first pumping systems were made in Italy and Switzerland since 1890 Since 1933 reversible turbines are used both as a motor-pump and as a generator of electricity, currently the obtained technical upgrading allow to get efficiencies up to 85%.

2.1.2 Thermodynamic accumulation

Thermodynamic accumulation is a recently introduced technology mainly used in association with concentration solar thermal systems. These plants operate at high temperature (up to 600°) and are suitable for the generation of electricity and/or heat process for industrial uses. Some parabolic mirrors focus sunlight on a receiver tube, inside which flows a special heat transfer fluid, which absorbs heat and carries it into a storage tank. The tank is connected through an heat exchanger to a generation system using steam turbines.

The heat transfer fluid, a mix of suitable salts, once heated maintains its high temperature (about 550° C) for some days, even not in contact with the heat source. This leads to energy production overnight or with bad weather. Thermodynamic solar plants are relatively simple and inexpensive, but require large spaces.

2.1.3 SMES and Flywheels

SMES (magnetic accumulator): The SMES, acronym of Superconducting Magnet Energy Storage, is a magnetic storage system and consists of a superconducting coil connected to the grid trough a reversible AC-DC converter. The coil is connected to a bridge rectifier that allows to conserve energy in the form magnetic.

$$E_M = \frac{1}{2} \cdot L \cdot I^2$$

If necessary, the energy stored in the superconducting coil can be instantly transferred back to the plant trough the inverter. This technology is still used only for big powers (above 1 MVA) but now it represent a quiet mature technology. One of the advantages of this technology is the possibility to storage large current instantly and release them quickly to meet such a drop in energy or brief blackouts in the utility grid [5], [6].

Flywheels: are electrical machines which can turn electrical energy into mechanical energy (kinetic energy) and vice versa. These systems can accumulate the energy of hundreds of kW for a long time and be recharged quickly. The rotors rotate at very high speeds, from hundreds to thousands of rpm and for this reason often they are referred to as super flywheels. The mechanical energy stored in the mass inertia of the rotor can be converted very quickly into a DC voltage, or a set AC voltages at the desired frequency.

2.1.4 Batteries

Accumulators (or secondary generators) are rechargeable electrochemical devices. After a discharge, during which (as in a battery) the combination of the reagents generates the reaction products and electric power, they are able to perform a recharge, in which, by suitably supplying electric power, reaction products are retransformed in the original reagents, storing energy. These systems may be cyclically charged and discharged a large number of times. Several different batteries exist, among them:

- **Lead Acid-batteries:** The lead-acid cell is the basic element of common accumulators. It delivers a very high current, is reliable, features a long operative life and works well at low temperatures. The anode is made of dust spongy lead (Pb) and a cathode of lead dioxide (PbO_2). In the modern accumulators an alloy of lead, which inhibits the electrolysis of water, potentially dangerous because producing hydrogen and oxygen gases and risk of explosion, is used. By contrast, lead-acid accumulators are bulky, while the lead is a toxic heavy metal. Moreover, mechanical stress may result in loss of capacity.

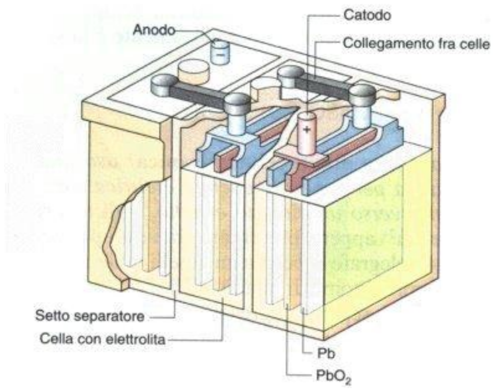


Figure 2.3 - Lead acid battery

- **NiMH batteries:** they represent an evolution of nickel-cadmium batteries, featuring a 30-40% higher energy density (Wh/kg or Wh/dm^3), and the elimination of the dangerous cadmium**.** They are light and powerful batteries, but disadvantaged by a noticeable auto- discharge phenomenon.
- **Lithium batteries:** they do not show memory effect and are more powerful than traditional batteries. Unfortunately also the cost is higher. They are largely used in low power portable devices such as cellular phones. The solvent may be flammable

- **Zinc-Air batteries:** belong to the category of fuel cells, where zinc is the fuel and oxygen is the oxidizing**.** They feature a lower cost if compared to Lead-Acid accumulators, an high energy density (from 7 to 10 times that of a Lead-Acid accumulator) and do not contain toxic heavy metals. They also feature a long duration (especially when working at high temperatures) and an high safety level (they do not blaze if damaged). On the other hand, they cannot be recharged by the user as the zinc dioxide must be regenerated in special plants. Their performance is also heavily influenced by temperature, humidity and air pollution.

- **Nickel-Zinc batteries:** particularly suitable for electric vehicles applications, due to a light weight and a large output power**.** They feature an high energetic density, reach 60% of a full charge in 1 hour, do not contain toxic materials and do not suffer of memory effect. On the other hand the typical number of charge cycles is low (600-800), and the running in phase is critical for the performance

2.1.5 Fuel-Cells + Electrolyser

A fuel cell differs from an accumulator in that the flow of reagents comes from the outside, such a system is therefore able to supply power without interruption as long as the flow of reagents is maintained. The basic principle of fuel cells is the generation of an electromotive force from combination of reagents (in the simplest case hydrogen and oxygen) through an electrochemical reaction, similarly to electric batteries. It is possible to reach an efficiency higher than 40%, even on small devices. Some fuel cells show also co-generation capabilities, further improving the overall energy efficiency.

Fundamentally 6 classes of fuel cells today exist and are classified into two categories: low temperature cells and high temperature cells.

2.1.5.1 Low temperature fuel cell

Polymeric electrolyte cells: they operate at relatively low temperature (60-90° C), featuring an efficiency as high as 50-60% and high power density (>1kW/kg). These features have made these cells attractive for transport applications road and, to date, are under testing exclusively in this area.

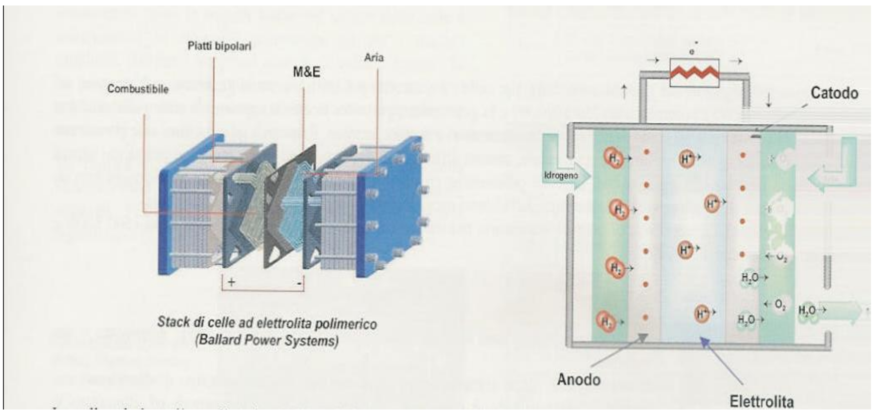


Figure 2.4 - Particular of a fuel cell

Alkaline cells: the electrolyte is composed by an aqueous solution of potassium hydroxide, operating between 70 ° C and 120 ° C with efficiency greater than 65%. They feature a considerable long lifetime (10000-15000 hours). One disadvantage of these cells is the need to use a fuel (H_2) very pure (99.99%) to preserve the integrity of the electrolyte, the cathode must also be fed by highly pure oxygen (99.99%) . originally developed for space applications, they have few applications in other fields.

Phosphoric acid cells : the electrolyte consists of a concentrated solution of phosphoric acid operating at around 200 ° C. They are suitable for cogeneration with efficiency of about 60%. They feature a considerable long lifetime (10000 -15000 hours). Today the more mature technology, but expensive.

Direct methanol cells: use methanol directly into the anode. The electrolyte is composed of a polymer membrane as PEM cells. Their operating temperature is between 70 ° C and 100 ° C. Currently, the efficiency is around 35%, while the power density is about 180-250 mW /cm^2. They are suitable for low power applications, represent a viable alternative to the traditional batteries in electronic portable devices.

2.1.5.2 High temperature fuel cell

Solid oxide fuel cell: they work at high temperature (900 ° C - 1000 ° C), the electrolyte are realized with ceramics materials. They are more durable and robust than cells with liquid electrolyte. The fuel (natural gas, biogas or coal gas) can be fed directly to the anode without being "reformed". The gas flow at high temperature made available to the discharge of the cell, allows the construction of installations combined with gas turbines and obtain efficiencies over 70% (Siemens Westinghouse). They are very promising for static generation, although burdened by high operative temperatures.

Fused carbonates cells: cells working at high temperature (650 ° C) using a solution of alkaline carbonate (at operating temperature of the cell) as electrolyte. Reaction kinetics are much faster than the cells at low temperatures and do not require the use of precious metals as catalysts. Have the ability to directly power the cell with natural gas or light fuel without the stage of reform of the external fuel also have the opportunity to combine a microturbine. The efficiencies are of the order of

60-70%. Able to produce temperatures of industrial interest and therefore suitable for co-generation.

2.1.5.3 Electrolyzer

An electrolyser is substantially an electrolytic cell that, respect to a fuel-cell, performs the inverse operation. In this system, in fact, a chemical reaction causes the electrolytic transformation of electricity into chemical energy, producing hydrogen and oxygen. Modern alkaline electrolysers operate at 120 ° and pressures up to 30 bar. This drastically reduce the size, while increasing the rate of production of hydrogen and also improving the efficiency. Alkaline electrolysers are mainly used to produce hydrogen on an industrial scale even they are also available in small sizes. The main drawback of these systems is a cost too high to permit a large diffusion.

The fuel cell + electrolyser system may be seen as a high-efficiency accumulation device. The electrolyser allows in fact to accumulate energy under the form of hydrogen when an excess of power takes place, while the fuel cell allows the re-transform the stored hydrogen into electric power when a deficit of available power is detected. By also storing the oxygen produced by electrolysis it is also possible to increase the efficiency of the fuel-cell feeding it with oxygen rather than with air. Such a possibility has however to be accurately evaluated due to the cost and complexity of the oxygen storage system.

The fuel cell + electrolyser system allows to decouple the production of energy from renewable sources by the availability of the primary power, with the additional possibility of integration with low or zero emission mobility systems. The high energy storage density suggests the use of such systems in applications requiring high accumulation capacity but a relatively low power.

Hydrogen storage is today possible according to different physical or chemical principles. In particular the following technologies are available:

High-pressure (200-250 bar) tank at ambient temperature: the storage of the hydrogen at ambient temperature and low pressures is quite unpractical, because of the excessive volume of the tanks. Therefore, in order to save space it is necessary to increase the pressure up to 200 bar or more.

Cryogenic accumulators: the storage of the hydrogen in liquid form allows to reduce the size of the accumulation system, however it requires cryogenic temperatures that only can be reached through a procedure of mechanical compression and cooling requiring a noticeable amount of energy.

Accumulators with absorbent materials: hydrogen in form of molecules in the gaseous state may be captured into absorbent materials such active coal or carbon nanostructures. However, it is necessary to cool the absorbent material up to -200°C to reach specific stored energy levels of practical interest.

Accumulators with metallic hydrides: hydrogen may be chemically combined with different metals and metallic alloys, forming hydrides. In this form the hydrogen can be trapped at relatively low pressures. Major problems of metallic hydrides accumulators are the weight and the low store capability**.**

2.1.6 Regenerative fuel-cells

Regenerative fuel-cells can be used to produce hydrogen from electricity and to generate electric power from hydrogen and air as well. They therefore act as systems composed by separated fuel cells and electrolysers, but are formed by a single element. Regenerative fuel-cells are today under development and have not yet reached a degree of sufficient maturity. Power losses are higher in the fuel-cell mode of operation and a total efficiency (round-trip) of 40-46% is reached with a 500mA/cm2 current density. This is satisfactory if compared with the typical performance of separate fuel-cell and electrolyser system, although the cost is much higher.

2.1.7 Flow batteries

Flow batteries are a special class of batteries where a large amount of electrolyte is stored in external tanks and driven through a the galvanic cell by pumps or exploiting the force of gravity. Such batteries are charged as normal batteries, but the energy, rather than be stored by the electrodes, is supplied to the electrolyte [7].

Flow batteries may have an extremely high capacity and are used in large systems as accumulators for naval applications, or storage stations. They feature an high efficiency, long life time, easy scalability and negligible environmental, while are burdened by a low energy density if compared with other accumulation devices.

Zinc-Bromine and Vanadium redox batteries are examples of flow batteries commercially available. The last, also said VRB-ESS, use the oxidation – reduction of the vanadium, to convert chemical energy into electric power and vice versa. A VRB-ESS system is made of two electrolyte tanks, respectively containing vanadium in two different states of oxidation (positive: V(IV)/V(V) redox couple, negative: V(II)/V(III) redox couple) and a stack of PEM cells.

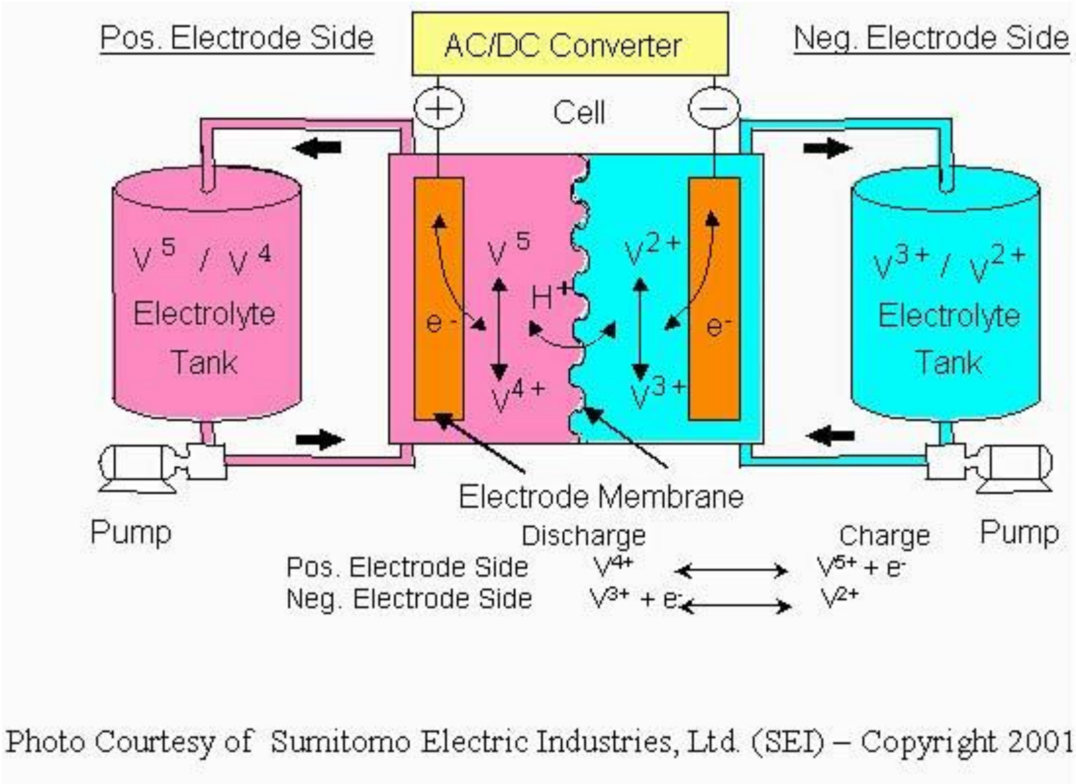


Figure 2.5 - VRB Energy storage system scheme

The two fluids are put in circulation by two pumps, in order to cross the stack of PEM cells. When the charged electrolyte crosses the stack, the electrons transferred by the different ionic forms of the vanadium across the membrane are forced to flow in an external electric circuit. Vice versa, by forcing a current in the stack through an external power source, the inverse process take place and the recharged electrolyte is pumped back in the tanks. A VRB -ESS system can be cyclically charged and discharged more of 10.000 times, moreover, thanks to the relatively fast kinetics of the redox couple high efficiencies can be obtained, without the use of expensive catalysts.

VRB -ESS systems can be easily expanded. In fact it is possible to increase the storage capacity simply increasing the size of the electrolyte tanks, while it is possible to increase the rated power by adding new cells to the stack.

These systems work at low temperatures and ensure a power availability higher than 98%.

2.1.8 Supercapacitors

Are devices designed to provide an high power for short time periods (few minutes), and to be recharged very quickly. They can be used to balance load peaks, or to complement conventional batteries in high dynamic storage systems [8].

Supercapacitors are not suitable to supply power for long times because of an energy density much lower than that of conventional batteries. On the other hand, supercapacitors feature an expected lifetime much longer than conventional batteries and a higher efficiency.

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

Figure 2.6 - Main features and typical applications of different accumulation technologies

2.2 Renewable energy sources – Overview

A form of energy is considered renewable if its source is regenerative or not "exhausted" in the human time scale and whose use does not affect natural resources for future generations. Generally are considered "renewable energy" the sun, the wind, the sea, the geothermal while a "non-renewable” resource is a natural resource which cannot be produced, grown, generated, or used on a scale which can sustain its consumption rate. Fossil fuels (such as coal, petroleum and natural gas) and nuclear power (uranium) are examples. These resources often exist in a fixed amount, or are consumed much faster than nature can create them.

In this context there is often a distinction between renewable "classic" (mainly hydroelectric and geothermal energy) and "new" renewable sources, such as solar, wind and biomass. In the context of electricity, renewable sources are also classified into "programmable sources" and "non-programmable sources", as they can be scheduled on demand for energy or not. According to the definition of the Gestore dei Servizi Elettrici (GSE) the first group includes hydroelectric plant with reservoir and basin, solid waste, biomass, plant treated using fossil fuels, fuel or process residues, while the second group (non-programmable) are flowing hydroelectric plants, wind, geothermal, solar, biogas.

2.2.1 Geothermal energy

Geothermal energy is produced using the heat, partly originated during the formation of the planet and in part produced by the decay of radioactive isotopes present in rocks of deepest parts of the globe. This heat is constantly transferred from the earth to the surface through convection of magma or water; because of this heat flux, the temperature of rocks increases by about 30 ° C per km(geothermal gradient). Rainwater, deeply infiltrating, flows underground through porous rock and becomes warmer, sometimes up to high temperatures, and sometimes till becoming steam. The geothermal fluid (water or steam) is transferred to the surface through a mechanical perforation (geothermal wells), so after some treatments, is sent to user plants (production of electricity in geothermal power plants or direct use).

Geothermal energy has several advantages:

- it always available locally and easy to use;

- do not produce pollutants or increase emissions of carbon dioxide or other gases in the area affected by geothermal manifestations;
- no risk of fire or gaseous emissions as there are no fuel of any kind (gas, oil or derivatives);
- provides heating, cooling and hot water every day for 24 hours;
- no maintenance required;
- no noise.

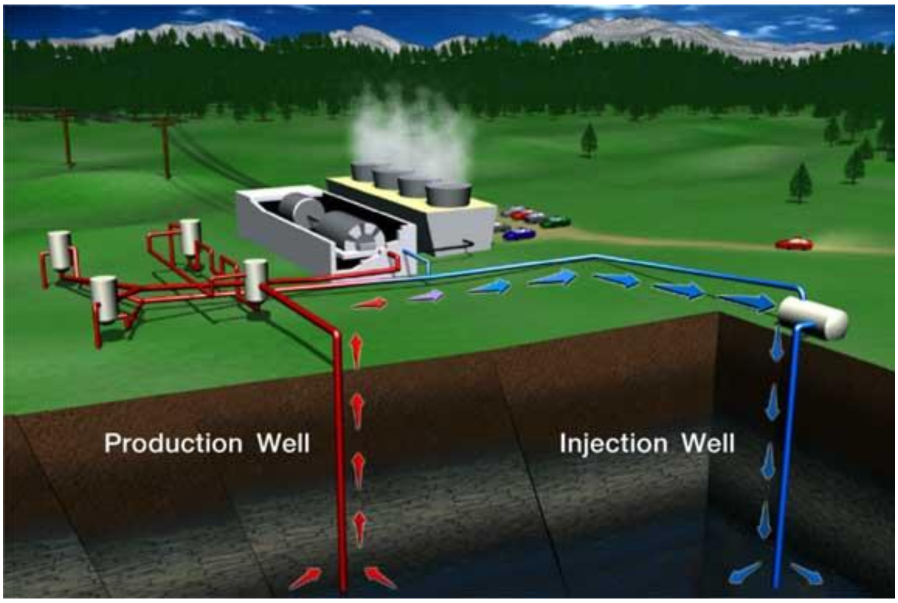


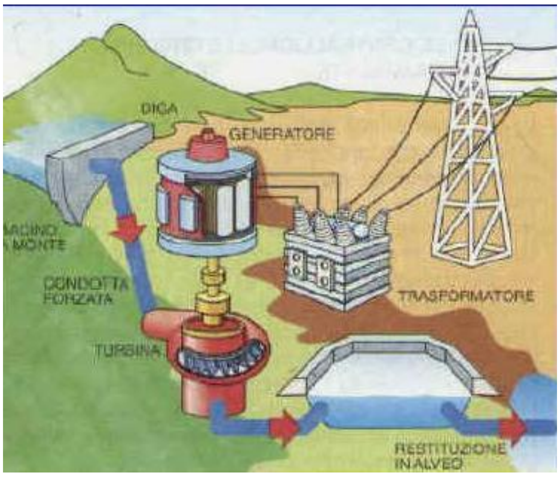
Figure 2.7 –Geothermal energy plant scheme.

However, this form of energy also has some negative aspects:

- a geothermal plant is more expensive than a conventional and recovery times are extremely long in contrast to the considerable reduction in operating costs;
- it has some adverse effects on the environment pollution due to geothermal fluids and seismic problems (areas with geothermal sources are often seismic) and there is a subsidence and seismic effects induced by the exploitation of the fields;
- requires the use of heat pumps with continuous energy consumption.

2.2.2 Hydroelectric Energy

Hydroelectric power is derived from the course of rivers and lakes through the creation of dams and pipelines. The water of a lake or reservoir is transported through pipelines downstream, transforming its potential energy into kinetic energy through the distributor and the turbine. A hydroelectric power plant is a complex machinery that conveys volumes of water from a higher to a lower altitude, to exploit the potential hydraulic energy, usually a river, that is converted into electrical energy.



2.8 - Hydroelectric power plant scheme

A hydropower plant consists of a water collection system at the highest altitude, water transport facilities (pipelines), equipment that transform hydraulic energy into mechanical energy (turbines) and then in electrical (alternator + transformer).

Hydropower is a clean and renewable source of energy, produces no harmful emissions (pollutants, dust or heat) or noise. However, the construction of dams and large reservoirs, with the flooding of vast land, may cause disruption of the ecosystem with enormous environmental damage.

2.2.3 Energy from the sea

Sea is a potential source of renewable energy. Different solutions for the exploitation of several natural phenomena occurring in the sea are being studied and / or are under testing. It is possible to convert into electricity at least three types of energy in the sea:

- tidal current energy;
- wave energy;
- salt gradient energy;

2.2.3.1 Tidal current energy

Among different renewable energy source, the tidal current energy is one of the most interesting and unexplored sources. In Europe, for example, the availability of this energy is approximately 75 GigaWatt. The turbines for the exploitation of marine currents may be (as for wind technologies) with horizontal or vertical axis. Even the technology of marine current generators is far to be mature and some major technical problems must be still solved, a promising solution has been recently proposed, based on the Kobold turbine concept.

2.2.3.2 Salt gradient energy

Saline gradient energy also known as osmotic energy is energy obtained from the difference in salt concentration between seawater and freshwater (eg the mouth of a river). It is possible to obtain energy from salinity gradient using two different methods: the electro reverse dialysis, also said osmosis, and Pressure Retarded Osmosis (PRO). Both are based on osmosis obtained by membranes for specific ions. Many laboratory tests have confirmed the effectiveness of osmosis for the production of energy. In the past years the cost of the membrane could become an obstacle to the development of this technology, today a new cheaper electrically modified polyethylene membrane is available ideal for a potential commercial use.

2.2.3.3 Wave energy

There are various techniques to exploit the wave movement. A known example is the Pelamis turbines (tested in Portugal), consisting of tubular structures floating while anchored to the seabed. Within the structures, the turbines are moved by water moving in and out from the structures to the rhythm of the waves where the generator is located. These generators produce energy constantly, take up a large amount of space.

Main advantages are low environmental impact (offshore plants), high availability of the primary resource and high degree of predictability. On the other hand technologies are not mature and the costs are still to high.

2.2.4 Biomass energy

The term biomass means any vegetable or animal organic form from which it is possible to obtain energy through thermochemical or biochemical processes. Biomass are made from waste biomass production activities. Instead, energy crops require the selection of species most suitable for energy production in order to maximize energy efficiency and minimize the production cycle. Biomass is the most sophisticated form of solar energy storage.

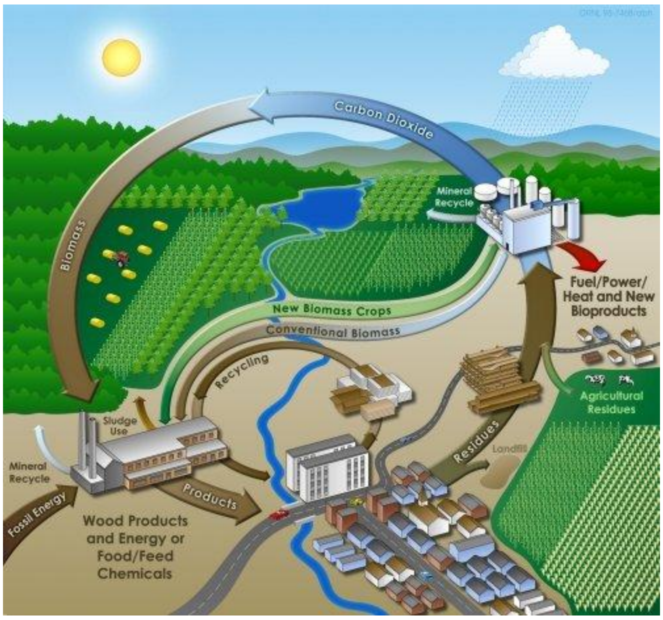


Figure 2.9 - Biomass cycle

Through the process of photosynthesis, plants absorb carbon dioxide and convert it into glucose, each mole of glucose has an energy content of 2872 kJ. It is considered a renewable and inexhaustible resource, if used properly, or if the usage rate does not exceed its regenerative capacity. Biomass can be used directly as fuel or converted into other substances (solid, liquid or gas) that are easier to use in conversion plants.

Biomass Energy doesn’t cause the increase of CO_2 in the atmosphere, because the amount of gas released during their combustion is the same as that absorbed during

growth through photosynthesis. Stating that the biomass is renewable with no environmental impact is a big stretch, but it is certain that emissions are below the values recorded in the case of traditional fossil energy sources.
However, these fuels have economic and technological problems due to their specific properties.

2.2.5 Solar energy

Solar energy means energy, thermal or electric, produced directly using the radiant energy emitted from the Sun to the Earth. Thermonuclear fusion reactions that occur inside the sun release enormous amounts of energy in the form of electromagnetic radiation. Part of this energy, after passing through the atmosphere, comes to the ground with an intensity of about 1.000W/m2 (radiation on a clear day at noon.) The average solar radiation, the European latitudes, about 200 watts per square meter. However, only a portion of this energy can be used, since it is necessary to collect it from large areas in order to have a significant amount. Solar energy can be used to generate electricity (solar photovoltaics) or heat (solar thermal and thermodynamic).

2.2.5.1 Solar thermal

Solar thermal technologies include all those in which solar radiation is used to heat thermal energy derived from solar radiation can be "captured" in many ways and used for the various energy needs: as heat for the production hot water for sanitary and heating, but also for cooling energy, electrical or mechanical. Current technologies also allow combined several types of energy.
A solar heating system consists of the following elements: a solar collector (known as "solar panel") which captures the sunlight and converts it into heat; The tank that stores the heat generated to make it available when needed; collectors are crossed by a fluid that is able to carry the heat received from the sun to thermal transfer and storage systems; the security components (pump, expansion tank, safety valves, etc..) manage the operation of the entire system.

The most important benefit is the reduction of pollution. Compared to a traditional system, in fact, the use of solar collectors enables reduction of air emissions to 70%. In addition, no toxic, flammable or otherwise dangerous elements are used: the whole system is not a source of risk or noise . Solar thermal collectors have a number of problems. First of all, their inability to function in the absence of sun so it is essential to integrative solutions.

2.2.5.2 Solar Thermodynamic energy

The Solar Thermodynamic or concentrating solar power is a technology using solar energy to generate electricity for practical applications. It can provide heat to medium and high temperature (up to 600°), allowing use in applications for electricity generation and / or process heat for industrial uses.This technology is used exclusively for industrial plants, that produce high-temperature heat and thus need to concentrate large amounts of sunlight onto a small area.The advantage found in the immediate time than the typical PV system consists of a continuous production of energy, even at night or during bad weather, thanks to a salt-based fluid that, when heated, retains its high temperature (about 550 ° C) for several days without being in contact with its source. Most of current commercial systems use parabolic trough collectors and a synthetic oil as heating fluid, which allows operating temperatures up to 400 ° C, limiting the thermodynamic efficiency.

2.2.5.3 Photovoltaic energy

Photovoltaic technology is able to transform directly and instantly, the energy associated with solar radiation into electrical energy. It uses the photovoltaic effect, based on the properties of some semiconductor materials which, if properly processed and interfaced, are able to generate electricity when hit by sunlight.

The basic component of the photovoltaic array is the cell, consisting of a thin slice of a semiconducting material, usually silicon properly treated, of thickness of 0.3 mm about. The main technologies currently used in the panels are based on silicon (60% using the monocrystalline silicon, polycrystalline silicon 25% and 11% amorphous silicon).

To reduce the cost of cells, new technologies are currently object of study using amorphous silicon and thin-film cells, in addition to other polycrystalline materials such as copper indium selenide of cadmium and tellurium. Everything indicates that these thin-film cells will fill most of the early disadvantage in terms of Wp/m^2, making it more economical. Modularity of photovoltaic panels allows a wide flexibility of use: the cells can be connected in series or in parallel to obtain the desired voltage (for cells connected in series the voltages are additive, cells connected in parallel to the currents are additive).

Photovoltaic technology offers special advantages. It can be used anywhere and can be produced wherever it is needed and in quantities close to the actual demand, thus avoiding losses due to transportation. There is a wide range of applications, from a few milliwatts for the pocket calculator, till a dozen of megawatts for power and the power plant can be modified at any time without problems. Besides it produces no pollution of any kind.

A photovoltaic system has a considerable initial cost, which varies by location and consumers' needs. It is heavily influenced by weather conditions.

2.2.6 Wind energy

Wind power is the product of the conversion of kinetic energy of wind into other forms of energy. First of renewable energy for its cost-production, it has been also the first renewable energy source used by man.

A wind turbine consists of several parts:

- rotor
- braking System
- gearbox
- power generator
- transformer
- steel tower.

There are wind turbines of different shapes and sizes, and therefore power. They may have one, two or three blades of different length

Wind energy has the following advantages:

- is an inexhaustible and free, available in many areas of the earth;
- requires a rather simple and mature technology;
- allows a consistent performance over time;
- has a low cost of the generator;
- does not produce emissions.

Main problem of wind energy is its inconsistency, eg. 10,000 3 MW wind turbines can produce power very different: on a summer day of "Dead Calm", could produce only 1,000 MW, but in an autumn day, with winds strong and steady, can exceed 20,000 MW.

Chapter 3

Design criteria for energy storage devices for distributed generations system

3.1 Introduction

The availability of primary power of a renewable energy source, such as wind or solar energy, depends on weather and environmental conditions such as wind speed or insolation level on the ground. To ensure the minimum level of power continuity required to supply a generic network of electrical loads these systems must be integrated with energy storage devices. In particular, generation systems operating in island mode must be integrated with an energy storage system to compensate the differences between the availability of primary power and the power required by the load during the intervals of insufficient generation. Therefore, for distributed generation systems, sizing of the entire system has an important role [9].

Sizing is a multivariable and quite complex problem, due to non-linear characteristics of components.

In literature are proposed different criteria for sizing systems operating in the island mode but they do not seem to afford a fully comprehensive solution.

This chapter describes the two most common criteria for sizing energy storage systems underlining the advantages and limitations.

3.2 Analysis of technical literature – Overview

A first aspect that must be addressed is the unpredictability and discontinuity of the availability power of renewable energy sources.

Determination of environmental variables such as wind speed and the level of solar irradiation, which are directly related to the power generated, is a preliminary stage in sizing. For evaluation of these data different mathematical tools are adopted based of theoretical and empirical model. Available models, however, are complex and can predict the dynamics of quantities of interest only to narrow times.

An assessment of available power versus time for sufficiently long intervals, however, is necessary for the definition of each size criteria. In literature there are different assessment approaches but they are based, however, on processing of data previously collected from meteorological observation stations.

A first approach is to consider average values of diagrams of insolation and wind speed. For example, some authors assume the generating function an average daily profile calculated on a yearly basis or monthly average values.

Methodology neglects the occasional and transient phenomena that occur over short intervals of time and forces, then, to take strong factors of excessive size and / or provide auxiliary generation systems. Another possible approach is to use directly time series data collected by distributed weather stations.

The starting point is the assumption that the environmental conditions are cyclic. A solution is to analyze the statistical properties of time series to highlight behaviors recurring over time for different locations. The task is to determine the probability distributions of wind speed, solar irradiation or variables related to them for the whole year. The analysis shows in this direction confirm for the wind speed probability distribution as the typical Weibull distribution and Weibull (or Beta) type distributions for levels of solar irradiation.

Analysis of probability distributions is a quite common starting point of conventional design procedures. Probabilistic methods offer greater reliability than those using average data, but are characterized by significant computational costs and need archives of meteorological data of previous years.

Use of random variables can be particularly advantageous, because statistical properties can be considered valid for locations where meteorological observations were not made in the past. Other methodologies, more sophisticated but less common in the literature, are based on the consideration that the dynamics of certain environmental variables could be regarded as stochastic processes. This means that the wind speed, for example, is considered as a random variable. More suitable mathematical tools for such modeling are the "Markov chains" used to assess the probability that a variable may assume a specific value, on the basis of the analysis of a suitable set of previously assumed values. Analysis of daily availability of renewable energy sources is the starting point to size the system components. The selection of such devices must be related to a given objective function, which maximizes system performance (costs, weight, dimensions). In technical literature there are no explicitly defined criteria that connect characteristics of the generation system to the storage system, and generally approximate methods or numerical simulations are used.

A common method used in practical applications separately sets the size of the generating system and that of the storage system. The generation system is designed so that the monthly average power, calculated in the worst month, is equal to the average power absorbed by the load. The energetic capacity of the storage system is, however, scaled on the basis of a minimum period of autonomy (**N.A.D.** *Number of Autonomous Days*) that the integrated system should ensure at full load with just the energy stored, ignoring the contribution of the generated energy. Usually, the period of autonomy ranges from three to ten days, depending on the expected performance in terms of continuity of power supply required.

The N.A.D. technique features a remarkable simplicity of the entire sizing procedure and a good level of reliability proven by years of operation of such realized systems. For these reasons, this design criterion is also suggested by the IEEE standards and is adopted on a regular basis by some telephone companies for the installation of radio base stations (Telecom Australia). The drawbacks of this technique criterion are substantially related to an excessive over-sizing of the storage system that has an impact on costs of plant.

Recently a new technique was developed based on probabilistic considerations on plant availability. The basic idea is to define an index (**L.O.L.P.**, *Lost of Load Probability*) expressing the probability that at given time the system does not allow properly supply to the load.

$$LOLP = \Pr\left\{P_U(t) \le P_L\left(t\right)\right\} \qquad (3.1)$$

where P_U (t) is the maximum power that the combined system of generation and storage can provide and P_L (t) is the load power demand. The L.O.L.P. index also coincides with the ratio between the number of hours of power failure and hours of normal operation of a system.

For a given value of the L.O.L.P. index different system configuration are considered. For a given L.O.L.P. value the most convenient configuration is then detected by minimization of a suitable function (typically the cost).

The choice of the optimal value of the index depends on the desired system reliability and can be determined by a preliminary risk analysis (risk analysis). Most of the implementations prefer a numerical determination through intensive use of the Monte Carlo method. Using time series and probability distributions of wind speed and solar irradiation different configurations of system are simulated. For each configuration a value of the index is determinate. Different model could be adopted for the simulation of each part of the system. These are quiet complex and can reproduce the behavior of the entire system. Since the same index value may correspond to multiple configurations, a procedure detects the minimum cost configuration. Numerical analysis shows a close correlation between the size of the storage system and the size of the generation system. Such an analysis, however, does not allow to obtain explicit correlations to understand how the various quantities depend on system variables. The L.O.L.P. method reduces the oversizing of power generators from renewable sources as confirmed by positive experiences on prototypes.

There are several versions of the method sharing the basic idea, but are based on the definition and calculation of slightly different indexes (for example related to relationships between energy and not time). The extensive literature produced in recent years shows that the LOLP method is currently the most accredited. Drawback of LOLP are substantially related to the considerable amount of calculations involving the simulation of different system configurations under consideration. Another limitation of the method is that it gives results only implicitly and any directives of the project can only be extrapolated by calculation examples.

Another interesting alternative to traditional approach is a probabilistic index used to evaluate the availability of a system exploiting a renewable energy source to supply a load. This index is the **L.P.S.P**(*Lost of Power Supply Probability*) and it expresses the probability that in a interval of time (day, month, year) there is a lack of power load.

3.3 Loss of Power Supply Probability (L.P.S.P.)

The probabilistic index LPSP (Loss of Power Supply Probability) is an estimate, on a time interval, of a lack of load power supply occurring in a generation system operating in island mode. By definition the index is directly an assessment of the reliability of the system that takes into account the load demand profiles, the availability of primary energy source and, if present, the capacity and performance of charging and discharging of the storage system. The resulting evaluations lead to good results for the determination of the size of the storage system that ensures an acceptable continuity of load power supply. Typically values of this index below or equal to 0.0003, which corresponds to about one day of lack of load power in ten years, are considered sufficient.

A given period of time T is divided into N intervals and for each of these the amount of energy produced by one or more renewable sources is calculated. The energy produced is then compared with that required by the load in the same interval. If the difference of these two quantities is positive, then $E_g(k)>E_{load}(k)$, the surplus is used to charge the storage system taking into account the charging efficiency (it should be noted that this occurs only if the battery charge is not at its maximum value), viceversa, when $E_{load}(k)>E_g(k)$, energy is delivered by accumulation device. In this case, if the total energy available is not sufficient to provide power to the load, the Lost Power Supply of the i-th interval is evaluated as follows:

$$LPS(k) = E_{Load}\left(k\right) - \left[E_g\left(k\right) + E_{ESS}\left(k\text{-}1\right)\ \eta_{ESS} - C\min\right]\ \eta_{SPC} \qquad (3.2)$$

Where E_{load} (k) is the energy required by the load, $E_g(k)$ is the energy produced from renewable source, $E_{ess}(k)$ is the energy in the form of state of charge in the accumulator, multiplied by the efficiency of discharge η_{ESS}, η_{spc} is the efficiency of the conversion system, and C_{min} and C_{max} are the minimum and the maximum value of the state of charge allowed.

The flow-chart of the LPS calculation is shown in the following figure.

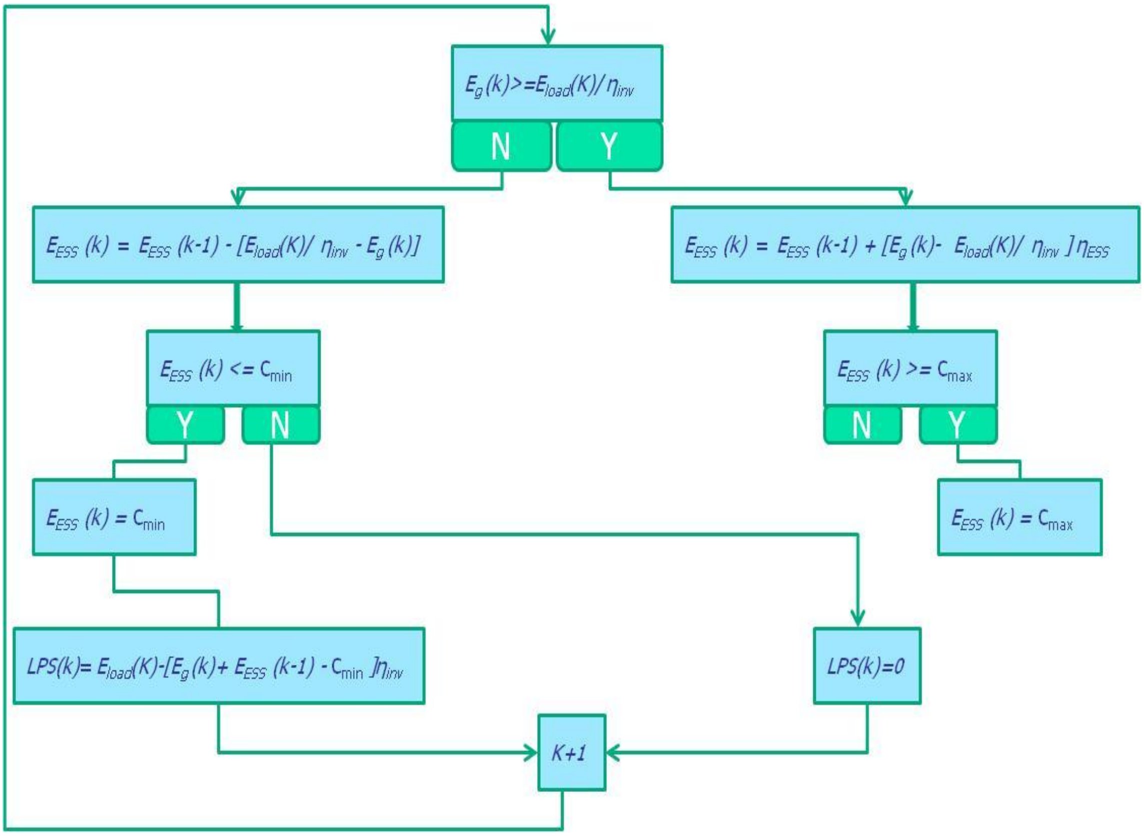


Figure 3.1 – Flow-chart of LPS

The total value of the index is then calculated as reported in the following equation:

$$LPSP = \frac{\sum_{k=1}^{N} LPS(k)}{\sum_{k=1}^{N} E_{Load}(k)} \tag{3.3}$$

The LPSP index is suitable to a wide range of analysis allowing evaluation in terms of energy and economy. Appropriate changes are then made on the basis of the considered problem.

In its original definition the index does not takes into account the rated power of the storage system but only the energetic capacity. For this reason, when possible solutions using flow batteries or fuel cells are analyzed, it is necessary to introduce another degree of freedom related to the system rated power. This limits the amount of energy that can be stored in a given interval when the energy produced is greater than the load requirement and the amount of energy released when there is an energy demand by the load. For this reason the index has been modified to consider the features of different energy storage systems. In these cases the power produced by the renewable energy source $P(k)$ is compared with the power required by the load $P_L(k)$.

If $P(k) > P_L(k)$ then the maximum amount of energy that can be stored in the storage system is $\left[P(k)-P_L(k)\right]\eta_{\mathrm{ESS}}\eta_{\mathrm{SPC}} * \Delta t$. This amount can be greater or lesser than the energy storage system rated power P_{ess}, so two different cases must be considered. If it is lower all the energy not supplied to the load can be stored but if this quantity is greater than P_{ess} than the difference $\left[P(k)-P_L(k)\right]-P_{ESS}$ it cannot be stored and must be dissipated trough dump load.

Another important issue must be considered. If $P(k) < P_L(k)$ and the energy required by the load $P_L(k)$ is greater than $\left[P(k)+P_{ESS}(k)\right]$ another LPS value is be calculated as reported in eq. 3.4.

$$\mathrm{LPS(k)} = \left[\mathrm{P_{Load}}(\mathrm{k}) - \left[P_{\mathrm{g}}(\mathrm{k}) + \mathrm{P_{ESS}}(\mathrm{k\text{-}1})\right]\right] * \Delta t \qquad (3.4)$$

This represent the amount of energy not supplied to the load due to an insufficient rated power of the storage system. As it is possible to observe this case is not considered on the traditional flow-chart of the index reported in literature. An exhaustive flow chart of the proposed LPS method is reported in the following figure.

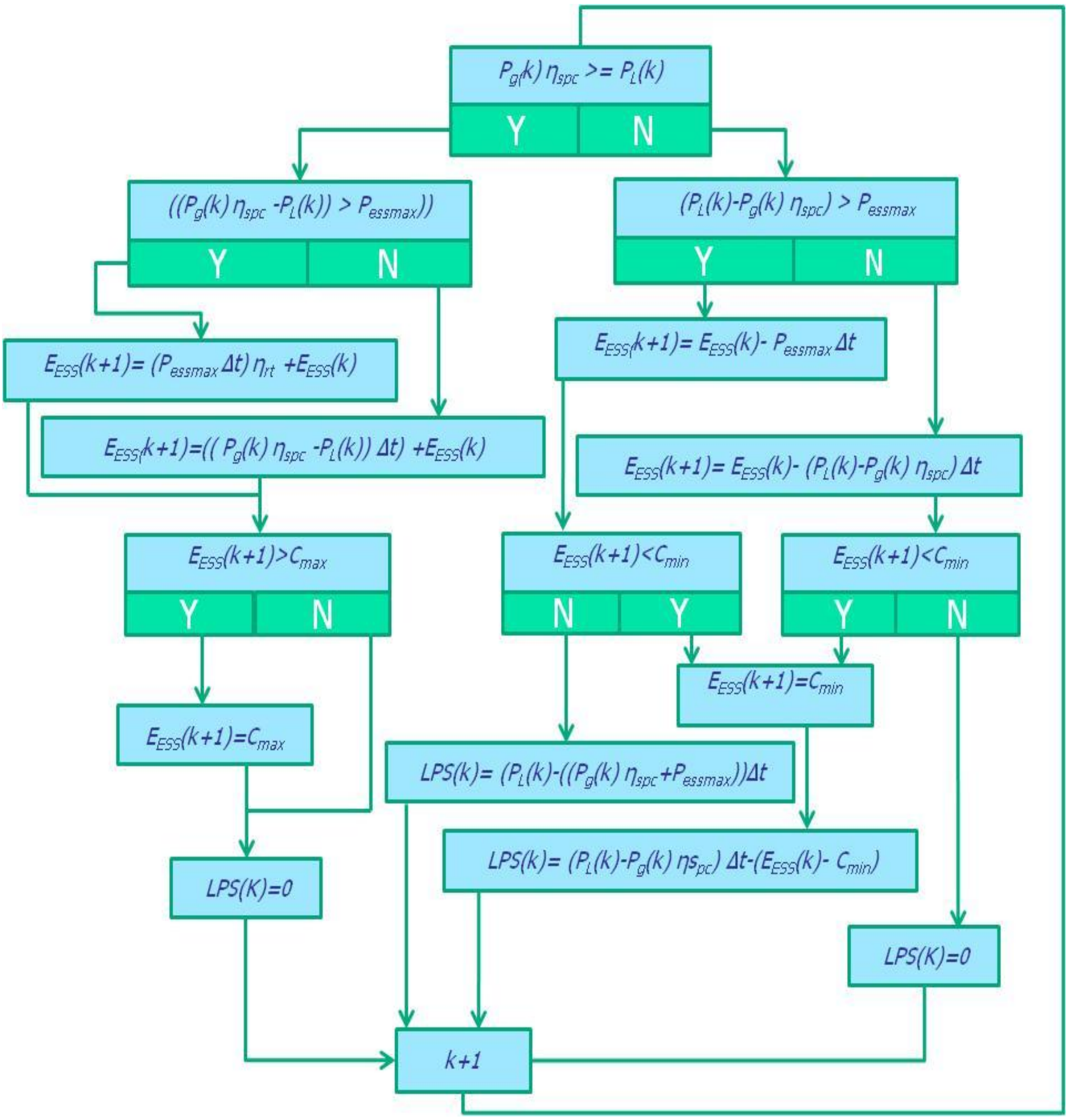


Figure 3.2- Flow-chart of the proposed LPS

Chapter 4

A VRB energy storage system for a tidal turbine generator

4.1 Introduction

Sun and wind are today the most exploited among renewable energy sources, thanks to the availability of quite mature technologies. However, tidal currents may represent an advantageous alternative, as they feature a power availability larger of both sun and wind, and they can be predicted with a much higher precision [10]. This makes easier the optimization of both generation plants and power lines, while reducing pay-back times and ensuring a better exploitation of power lines.

However, as other renewable energy sources, the power obtainable from marine currents is far to be constant, featuring a dominant daily dynamic and a secondary monthly dynamic. As a consequence, working alone, a system exploiting the tidal energy is not able to reach the minimum level of power continuity required by commercial, residential or industrial loads. Therefore, it must be complemented with suitable storage systems, or auxiliary power generators, in order to compensate for the differences between the available primary power and the power required by the loads. The energy produced from a plant exploiting marine currents can be stored and released when necessary using one among the several storage technologies today available. By suitably storing the produced power a new degree of freedom is achieved in delivering energy to the grid. Therefore, a better exploitation of the produced energy is obtained, while improving the system stability and making possible a more favorable design of underwater power lines connecting the turbine to the in-shore grid.

Among all the possible alternatives to equip a tidal generation system, Vanadium Redox Batteries are considered, as they represent an advantageous tradeoff among cost, maturity, reliability and sizes.
Specifically, this study analyses the application of Vanadium Redox Batteries on a 18 kW prototype tidal turbine, aimed to supply in island mode a set of domestic users. A design of the energy storage system is first accomplished according to a deterministic approach, also considering the autonomy of the system in case of fault of the turbine. A system analysis is then performed by simulation to confirm the consistence of the design. Optimization of the power size and the energy storage capability of the VRB storage system are finally discussed through a probabilistic approach.

4.2 Tidal turbine generator prototype

Even the technology of marine current generators is far to be mature and some major technical problems must be still solved, a promising solution has been recently proposed, based on the Kobold turbine concept [11], [12]. A 18 kW (25 kW peak power) prototype featuring a fully submerged vertical-axis multi-bladed rotor, has been realized, as shown in Figure 4.1, and is under test in the Messina Strait in Italy. The system can operate connected to the main grid, or as a standalone generation unit. It is equipped with an induction alternator, connected to the turbine shaft through a speed multiplier. A schematic of the generation system is drawn in Figure 4.2.

Figure 4.1 – picture of the Kobold turbine prototype

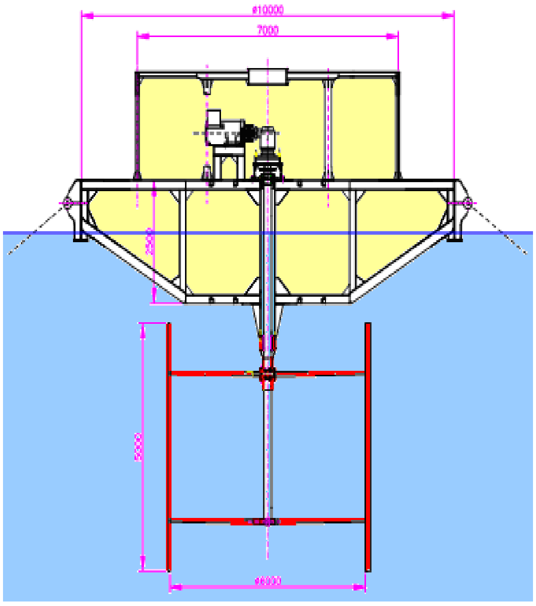


Figure 4.2 –Section of the Kobold turbine prototype

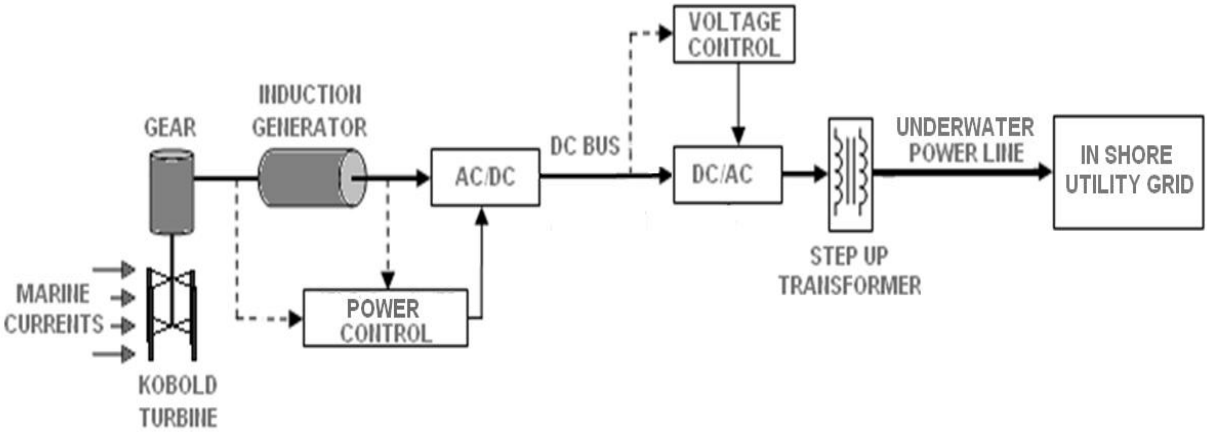


Figure 4.3 – Block scheme of the generator prototype

A typical time diagram of the marine current speed along a day in the Strait of Messina is shown in Figure 4.4.

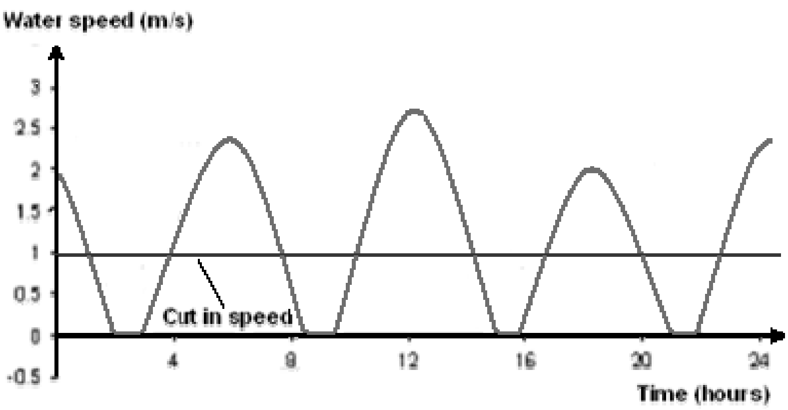


Figure 4.4 - Typical variations of water speed along a day.

Current speed oscillations feature a period slightly greater than 24 hours. The intervals in which the current is close to zero are caused by the periodical reversal of the flow direction. Marine current speed oscillations and reversal lead to a reduction of the theoretically available energy, as the turbine cannot work under its cut-in speed, set at 1 m/s. The amplitude of the current speed diagram shown in Figure 4.4 oscillates with a period of about 14 days, being related to the moon phase.

On the basis of field measurements of water current speed, it is possible to precisely estimate the daily, monthly and seasonal evolution of available primary power and the potential production of energy. The mechanical power produced from the turbine is given by:

$$P_{Turb} = \frac{1}{2}\rho V_W^3 S C_W \tag{4.1}$$

where: ρ is the water density, V_W the water speed, S the swept blade area and C_w the turbine power coefficient. According to experimental measurements a 0.06 power coefficient has been estimated for the considered case. Table 4.I deals with the estimation of the power generated during a three hours long periodical increment of the water speed. The power is on one side computed from measurements of turbine torque and shaft speed, obtained by a suitable instrumentation hosted on the prototype and, on the other side, estimated through eq. 4.1 from measured water speed. As it is possible to observe, the estimated power features a good correlation with the computed one.

Table 4.I: Measured and estimated turbine output power.

Time	**Measured turbine shaft speed *Ω* [Rpm]**	**Measured turbine shaft torque *T* [Nm]**	**Computed shaft power (*T* Ω*) [W]**	**Measured water current speed [m/s]**	**Estimated shaft power (eq. 1) [W]**
14.30	*0*	-	*0*	*0*	*0*
15.00	*1.59*	*888*	*0*	*0.5*	*0*
15.30	*3.18*	*3553*	*1000*	*1*	*999,7*
16.00	*4.77*	*7997*	*3395*	*1.49*	*3365*
16.30	*6.19*	*13344*	*7350*	*1.94*	*7353*
17.00	*6.20*	*14006*	*7729*	*1.95*	*7390*
17.30	*6.37*	*14221*	*8063*	*2*	*8014*

A time diagram of the output electrical power along a day can be obtained by combining the water speed diagram of Figure 4.4 and eq. 4.1, taking also into account the efficiencies of the induction alternator, of the speed multiplier and the power conversion system, as shown in Figure 4.5. As it is possible to observe primary power availability is not uniformly spread over the day. Moreover, the water speed periodically falls below the cut-in speed, making impossible to produce energy. Therefore, the system is not able to support a set of residential loads featuring typical load diagrams, even if the peak generated power is equal or greater than the peak load power and the generated energy is equal or greater than the energy daily required by the loads, as shown in Figure 4.6. VRB- ESS design.

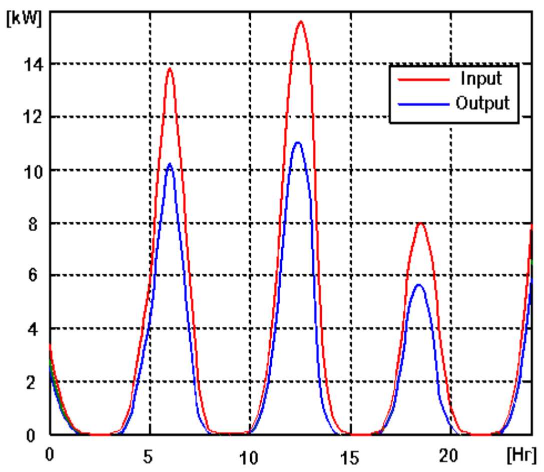


Figure 4.5 - Mechanical power and generated power.

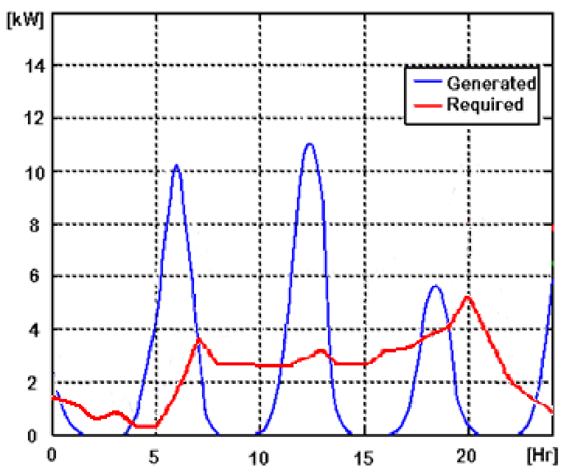


Figure 4.6 - Generated electric power and load power.

4.3 VRB- ESS design

The design of the VRB-ESS for the considered tidal turbine prototype requires the development of suitable mathematical models of the turbine generator and of the energy storage system. Non linear high-order mathematical models should be used to precisely simulate the dynamic of practical turbines and energy storage systems when taking into account power losses and control system operations. However, simplified mathematical models are generally sufficient to describe the behavior of generators and accumulators when dealing with simulations extended over long times. Hence, first order mathematical models have been selected to represent both the turbine and the energy storage system [13],[14],[15]. The schematic of the simulated system is shown in Figure 4.7. In order to ensure the stability of a standalone system the generated power P_s must be controlled and dispatched matching the load power demand P_s*. The net generated power P_s is obtained by composition of the turbine output power P_{Turb} and the power exchanged by the VRB Energy Storage System P_{EES}.

As it is possible to observe in Figure 4.7, the power error ΔP, given by the difference between the power supplied from the turbine and that required by the load, is sent to a PI regulator in order to adapt the output of the storage device according to the power demand. Parameters of the PI regulator have been selected to obtain a time response closely matching that typical of a VRB-ESS. Main parameters of the linear blocks are shown in Table 4.II.

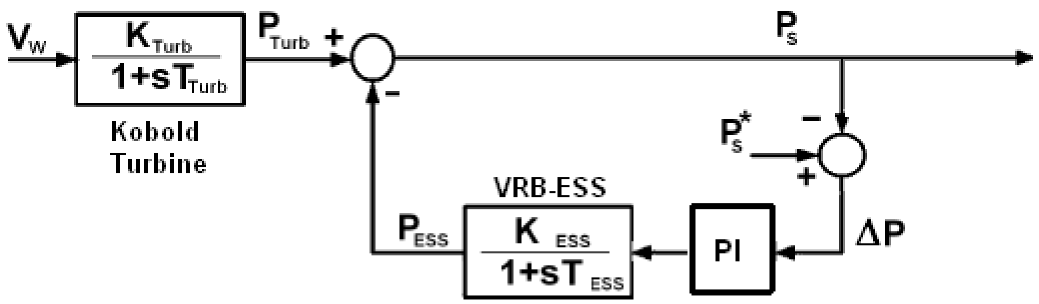


Figure 4.7 - Block scheme of the mathematical model of the generation system with VRB-ESS.

Table 4.II: Parameters of the mathematical model.

VRB-ESS	$K_{ESS}=-1$	$T_{ESS}=0.1$
Turbine	$K_{Turb}=1$	$T_{Turb}=1.8$
PI Regulator	$K_p=15$	$K_i=25$

In Figure 4.8 a simulation is shown dealing with a sudden load variation. from 0.1 to 0.2 p.u., while the turbine output power is kept constant. The storage device correctly responds to the load variation by inverting the power flow, switching from the charging mode to the discharging mode. The power equilibrium is reached in some hundreds of ms, well in accord with the practical behavior of a VRB-ESS.

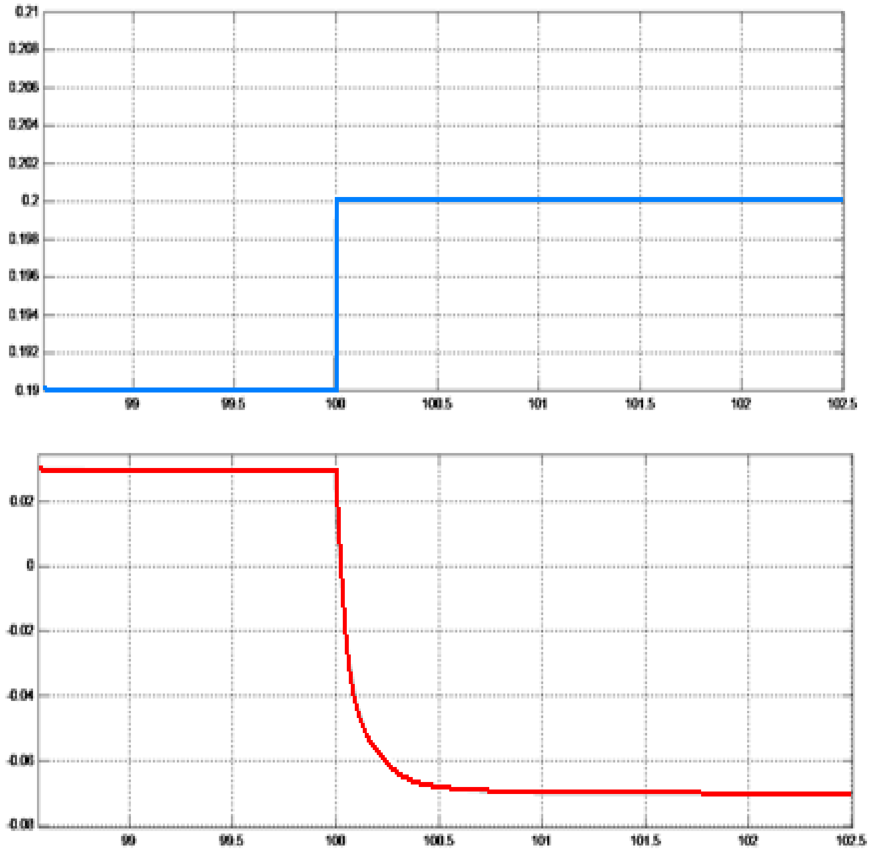


Figure. 4.8 - Load variation (up), storage device output power (down).

The developed model of the system can be exploited to perform the steady (or slowly varying) state sizing of the energy storage system using either deterministic approaches, either probabilistic strategies as the Loss of Power Supply Probability (LPSP) method.

A deterministic approach accomplishes a separate sizing of the generation system and the accumulation system. The selection of the size of the generation system can be done on the base of average available power in the case of the worse environmental conditions according to load power requirements. However, in the present case the generator is yet realized, therefore it constitutes the design starting point and the maximum sustainable load has been rather identified. The sizing of the accumulation system is then performed on the basis of time diagrams of available and load power, taking also into account system autonomy requirements in case of default of the primary source. Two reference cases are considered:

- Maximum load – Either the generated power diagram, either the power load diagram vary during the year due to seasonal variations of both the available primary power and the type and the number of load connected to the grid.

The maximum load condition corresponds to the day in which the maximum difference occurs between the generated and the required energy. In this case the power demand must be always satisfied, while ensuring that at the end of the day the State Of Charge (SOC) of the energy storage system is equal to its initial value (zero energy balance).

- Turbine shut down - Most of the analysis and design methods used in renewable energy source generation systems are based on the concept of power supply during a number of autonomous days (NAD). The storage system capacity is therefore determined on the basis of the energy required by the loads during the NAD. A 0.5 NAD, equivalent to a 12 hours interruption of the power production in condition of maximum load is here considered.

A steady state sizing has been first accomplished according to a deterministic approach. According to the water speed profiles in the Strait of Messina, the average energy daily produced by the Kobold turbine is around 75 kWh.A typical residential user, requires 16.6 kWh per day (average value for a residential user) with two power demand peaks between 8:00 and 10:00 am and 5:00 and 7:00 pm. The typical peak power is 1.1 kW. In the maximum load condition the energy and the peak power required by the user are 150% of the respective average value.

According to previous considerations, and assuming that all the extra power produced is stored and reused with a 70% round trip efficiency and that the SOC of the energy storage system at the end of the day is equal to its initial value, the prototype is able to generate energy sufficient to support three typical residential users, corresponding to 74.7 kWh with a power peak of about 5 kW.

Taking into account the maximum difference between generated and requested power along a day, a 10 kW VRB-ESS has been selected to cope with the maximum load case. Moreover, in order to ensure a perfect matching between available and requested electrical power, taking also into account limitations on maximum and minimum values of the SOC a 35kWh energy storage capability has been selected.

Simulations are shown in Figure 4.9 dealing with the behavior of a 10 kW, 35 kWh VRB-ESS, on the basis of the time diagrams of Figure 4.6, where the load diagram corresponds to the composition of the power drawn by three typical residential users in the maximum load condition. As it is possible to observe, the initial SOC corresponds to the final value, moreover the lower value of the SOC is 53% a quite acceptable and safe level. Finally in Figure 4.10 it is shown that at least four hours of autonomy are featured with the turbine not working until the SOC reaches a 60% level.

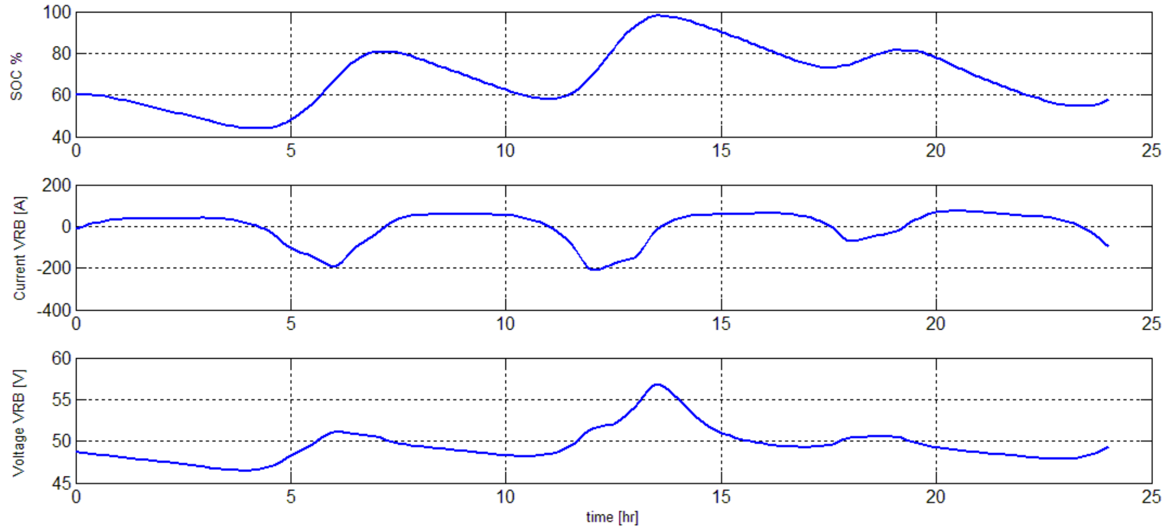


Figure 4.9 - Maximum load condition, 10 kW – 35 kWh VRB-ESS: SOC% (up), current (middle), voltage (down).

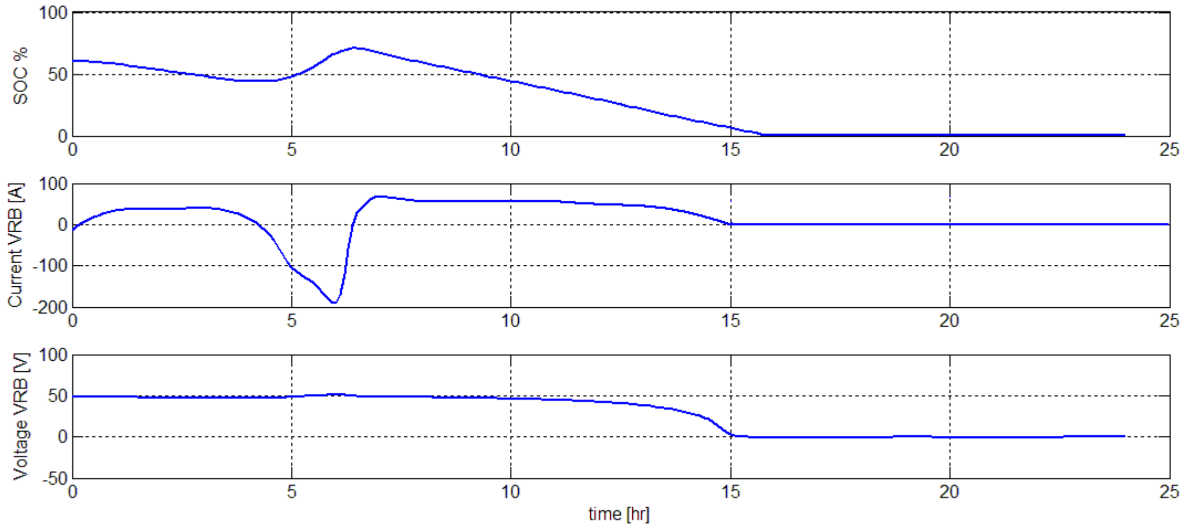


Figure 4.10 - Maximum load condition, 10 kW – 35 kWh VRB-ESS, with the turbine not working: SOC% (up), current (middle), voltage (down).

According to further simulations, a smaller energy storage capability would lead to larger stresses for the VRB ESS, as it would be subjected to discharge depths in excess of 60%, able to noticeably reduce the expected lifetime. Moreover, by reducing the energy storage capability some of the available primary power would be lost as the VRB ESS would easily reach the maximum SOC.

According to the second reference case the energy storage system must ensure at least 12 hours of autonomy in the condition of maximum load. Moreover a 60%

maximum discharge depth is allowed. Simulation results shown in Figure 4.12 demonstrates that a 75 kWh energy storage capability is sufficient to fulfill both requirements.

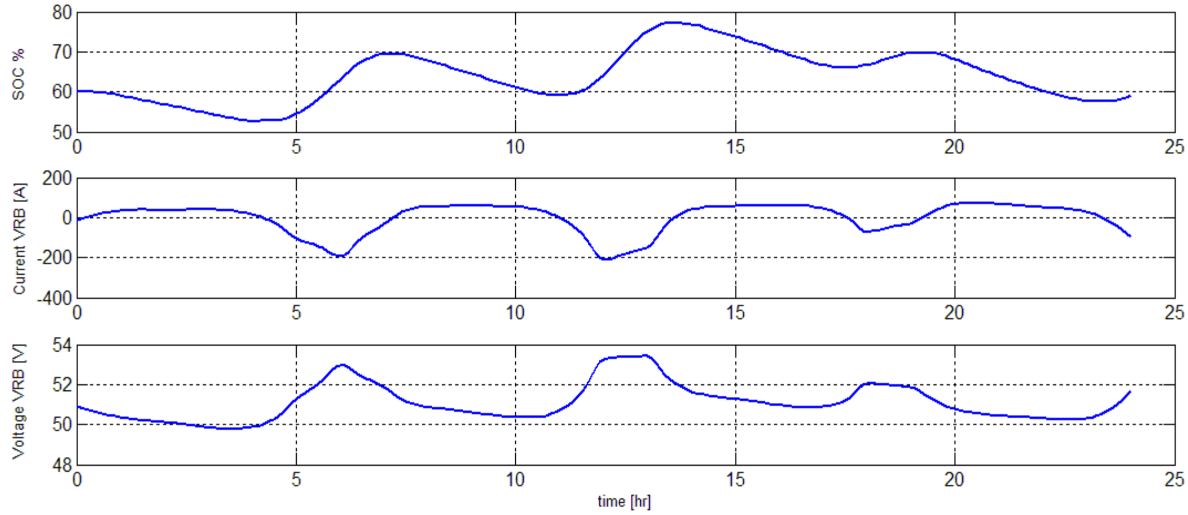


Figure 4.11 - Maximum load condition, 10 kW – 75 kWh VRB-ESS: SOC% (up), current (middle), voltage (down).

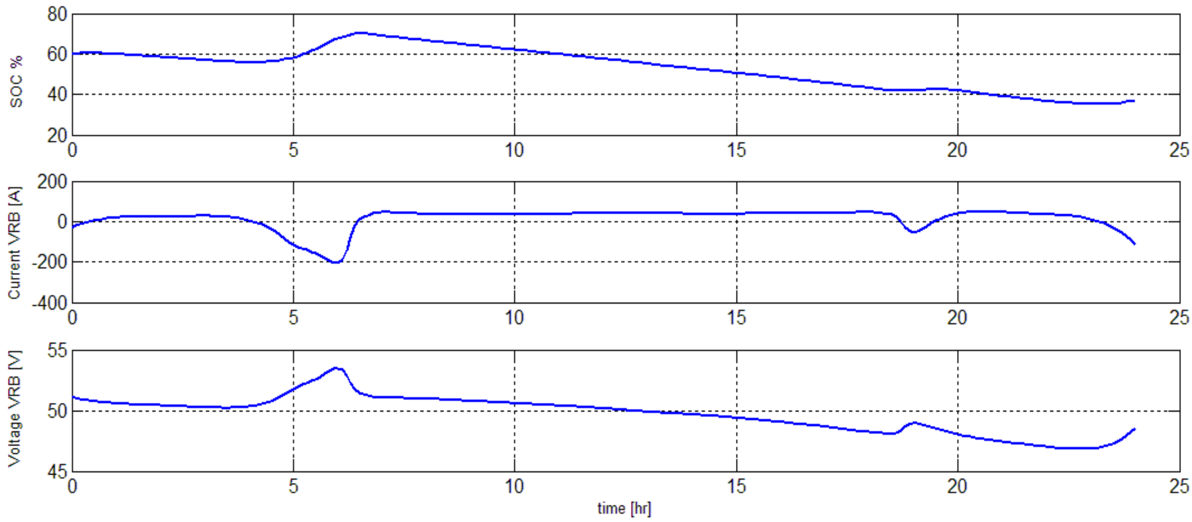


Figure 4.12 - Maximum load condition, 10 kW – 75 kWh VRB-ESS, with the turbine not working: SOC% (up), current (middle), voltage (down).

A Lead-Acid Batteries Energy Storage System (LAB-ESS) doing the same job would feature 96 kWh (28% more). In fact, the discharge depth of a LAB-ESS should not exceed 25%. Moreover, a LAB-ESS would cost no less than 35 k€, weighting 15.000 kg, while the considered VRB-ESS costs 39.7 k€ and weights 18.000 kg. Moreover, according to Table III a LAB-ESS features 1,200 cycles, while the replacement cost is

100% of the initial cost, as all the system must be replaced. Moreover, extra costs for recycling or disposing the exhausted system must be added. On the other hand, the VRB-ESS features a longer expected lifetime, while a full replacement costs only 25% of the initial value, as the electrolyte can be entirely reused.

Table 4.III: Comparison of VRB-ESS and LAB-ESS.

	VRB-ESS	***LAB-ESS***
Output Voltage Range	*56 V-42V*	*56V-42V*
Operating Temperature	*0°C-35°C*	*0°C-25°C*
Lifetime	*>10.000 cycles*	*1.200 cycles*
DoD (deep of discharge)	*60%-75%*	*20%-25%*
Efficiency	*65%-75%*	*30%-45%*
Charge to Discharge duration rate	*1,8:1*	*5,0:1*
Maintenance	*Yearly*	*Quarterly*
Replacement cost	*25%*	*>100%*

An optimal energy storage system design can hardly be obtained with the NAD method, as deterministic approaches, while simple to apply, inevitably conduct to a system over sizing. A more optimized design can be carried out through a probabilistic approach, which makes it possible to determine the minimum (and thus the most economical) storage system capacity on the basis of given system reliability requirements. The reliability of the system can be assessed using the Loss of Power Supply Probability (LPSP) method for given load profiles and primary power availability[16],[17].

LPSP is the probability that a loss of power supply occurs, meaning that the power supplied by the tidal generator and the VRB-ESS is not able to fulfill the power demand. According to the LPSP strategy a suitable index is defined to appraise the probability that system is not able to sustain the load.

LPSP gives the number of days the supply is lost over the given time period, according to different possible VRB-ESS designs, as shown in Figure 4.13. These diagrams can be exploited to optimize the energy storage design assuming *1.8 k€/kW* and *290 €/kWh* rates.

As an example, considering acceptable a 0.0003 LPSP, which means to have a loss of power supply of approximately 1 day in ten years, some different combinations of power and energy storage capability result suitable, as shown in Tab. 4.IV. Among them, the minimum cost is achieved by a *8 kW – 37 kWh* VRB-ESS. If compared with the results of the deterministic design approach a *10.7%* cost reduction is obtained.

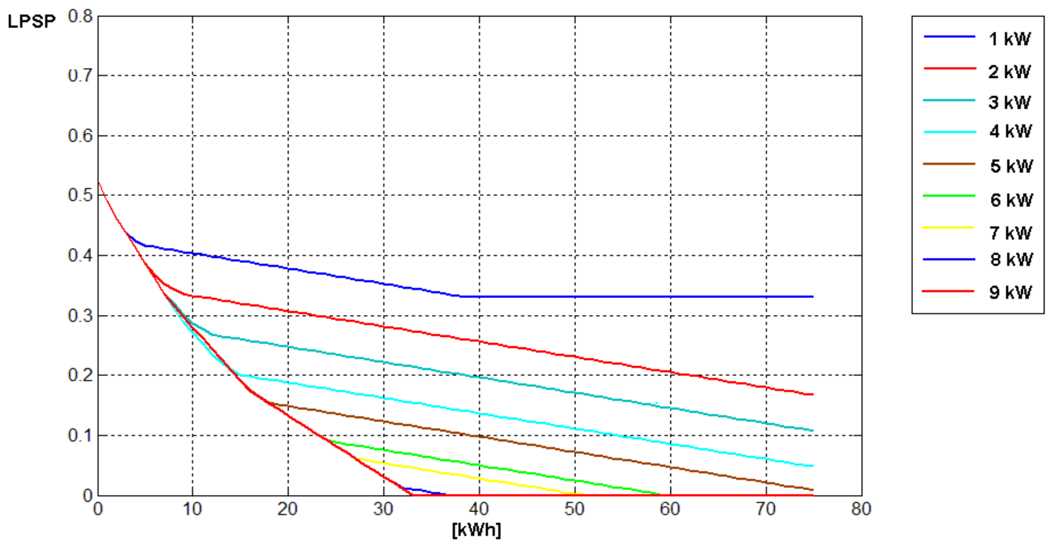


Figure 4.13: LPSP as function of the energy storage capability and the rated power of the VRB-ESS

Table 4.IV: Power and energy capability combinations suitable for LPSP=0.0003

Power [kW]	**Energy [kWh]**	**Cost [k€]**
6	60	28.2
7	51	27.39
8	37	25.1
9	34	26.0

4.4 Conclusions

This study has analyzed the introduction of a Vanadium Redox Batteries Energy Storage System on a prototypal 18 kW tidal turbine, aimed to supply in island mode a set of domestic users. According to a deterministic design approach a 10 kW, 35 kWh VRB-ESS has been selected to fulfill the requirements of three typical residential users. It has been also demonstrated by simulations that such an energy storage system enables the tidal turbine generator to effectively supply the considered load demand. Moreover by increasing the energy storage capability to

75 kWh, a 12 hours autonomy is reached. A detailed comparison between the considered VRB-ESS and a Lead-Acid batteries based system has been also carried out demonstrating the convenience of the VRB solution. A probabilistic analysis has been finally accomplished based on the LPSP approach showing that further costs reductions can be obtained by an optimal design.

Chapter 5

Optimal Design of Energy Storage Systems for Stand-Alone Hybrid Wind/PV Generators

5.1 Introduction

In stand-alone, or island mode, applications the most critical requirement for an electric generator is the reliability of the power production, in order to ensure a perfect balance between power demand and generated power. On renewable energy plants the reliability strictly depends from the availability of the primary resource over the time, which shows seasonal, daily or instantaneous variations. Among renewable energies, the wind undoubtedly is the more affected by variability, although, also photovoltaic plants are heavily influenced by weather conditions, moreover featuring a limited period of operation over the day. Therefore, both photovoltaic arrays and wind turbines working alone cannot ensure the minimum level of power continuity required to supply in island mode a generic set of residential loads.

Hybrid Wind/Photovoltaic Generators have been proposed and experimentally operated in order to improve the reliability of electric power generation in stand-alone operations [18]. In fact, by composing the time availability of sun and wind a larger and more continuous primary energetic source is obtained. A more sophisticated approach deals with the addition of suitable Energy Storage Systems (ESS) to stand-alone generators [19]. An energy storage system not only largely improves the reliability of the generated power, but it is also able to avoid grid instabilities, while reducing the size and the cost of the power lines serving Photovoltaic plants or wind turbines.

Energy Storage Systems featuring a wide range of technologies are today available. Among them traditional solutions are those based on: pumped hydroelectric storage, compressed air energy storage and lead acid batteries. Moreover, in the last years, some advanced technologies have been also developed including: flywheels, superconducting magnets, fuel cells with electrolyzers, Lithium ion (Li-ion) batteries and redox flow cells. The last two technologies, in particular, today appear very promising, requiring inexpensive infrastructures if compared with pumped hydroelectric and compressed air energy storage, while making possible to store energy on longer terms if compared with flywheels and superconducting magnets. Finally, Li-ion batteries and redox flow batteries are less expensive and more reliable than fuel cells and conventional lead acid batteries.

A probabilistic methodology is described in this work to determine an optimal design of the energy storage system for a stand-alone hybrid generator aimed to supply a set of residential loads. Lead Acid, Lithium ion and Vanadium Redox Batteries energy storage systems are considered. ESSs are analyzed through an LPSP (Loss of Power Supply Probability) approach, in order to detect the less expensive configuration ensuring the required level of supply continuity. To do this, the basic LPSP approach has been suitably modified to allow an independent setting of the rated power and energy storage capability. Obtained results are then exploited to accomplish an optimal design of the whole system.

5.2 Optimal design procedure

A hybrid generation system is a combination of a Wind Turbine (WT) generator, a Photovoltaic array and an Energy Storage System. Among some possible different structures, the basic scheme shown in Figure 5.1 it is assumed. According to such a scheme, the WT generator, the PV plant and the energy storage system are connected among them through an intermediate DC bus. The last being in turn connected to the AC loads through an inverter and a distribution network.

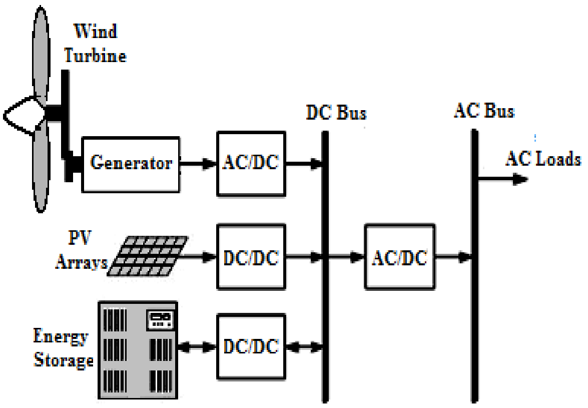


Figure 5.1 - Schematic of a Hybrid Wind/PV generation system.

The design of an hybrid generation system is a quite complex task as a given level of continuity of the power supply can be obtained by multiple combinations of Wind Turbines, PV arrays and energy storage capacity, although at different costs [22], [23]. A procedure is then proposed to accomplish an optimal design, taking into also account the availability of different energy storage technologies. A flow-chart of the proposed procedure is sketched in Figure 5.2.

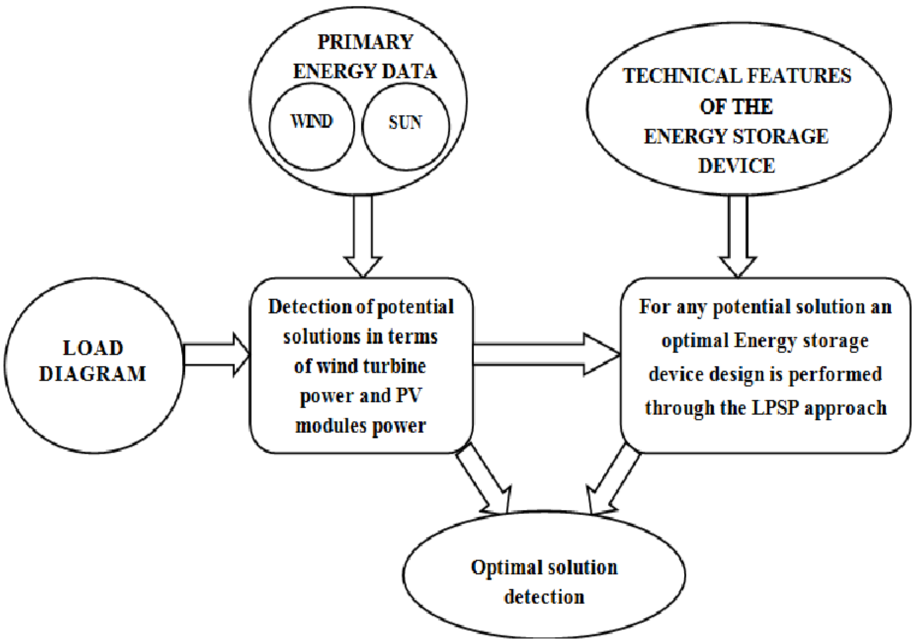


Figure. 5.2 – Flow chart of the developed optimal sizing procedure

The first step of the proposed procedure is an assessment of the available energy resources, on the basis of statistical data referred to the geographical site selected to allocate the hybrid generation plant. Power obtainable from wind and solar irradiation are then computed through suitable mathematical models and compared with the assigned load diagram to detect the minimum generation power required to satisfy the energy demand. Several combinations of wind turbines and PV modules arrays fairly lead to a sustainable energy balance. However, due to the discontinuity of the primary energy resources each potential solution also requires a suitable energy storage system to provide the required level of supply continuity. A probabilistic approach based on the LPSP index is then accomplished to detect for each potential solution the most suitable ESS design, taking into account the features of some different energy storage technologies. The most advantageous solution is finally detected by comparing the costs of all the potential solutions.

5.2.1 Load, wind turbine and PV plant models.

Daily diagrams of the power generated by a wind turbine and a PV module can be obtained from statistical wind speed and solar irradiation data. Starting from an average daily wind speed profile, as that shown in Figure 5.3, the mechanical power produced from a wind turbine can be calculated as:

$$P_{Turb}(t) = \tfrac{1}{2}\rho V_W^3(t) S_T C_W \tag{5.1}$$

where: ρ is the air density, V_W the wind speed, S_T the swept blade area and C_w the turbine power coefficient.

On the basis of a solar irradiation profile, as that shown in Figure 5.3, the output power of a PV array can be calculated as follows:

$$P_{PV}(t) = Irr(t) \times S_{PV} \times \eta_{PV} \tag{5.2}$$

where: S_{PV} is the area of the PV arrays, *Irr(t)* is the solar irradiation and η_{PV} is the global efficiency of the solar cells and the power converters.

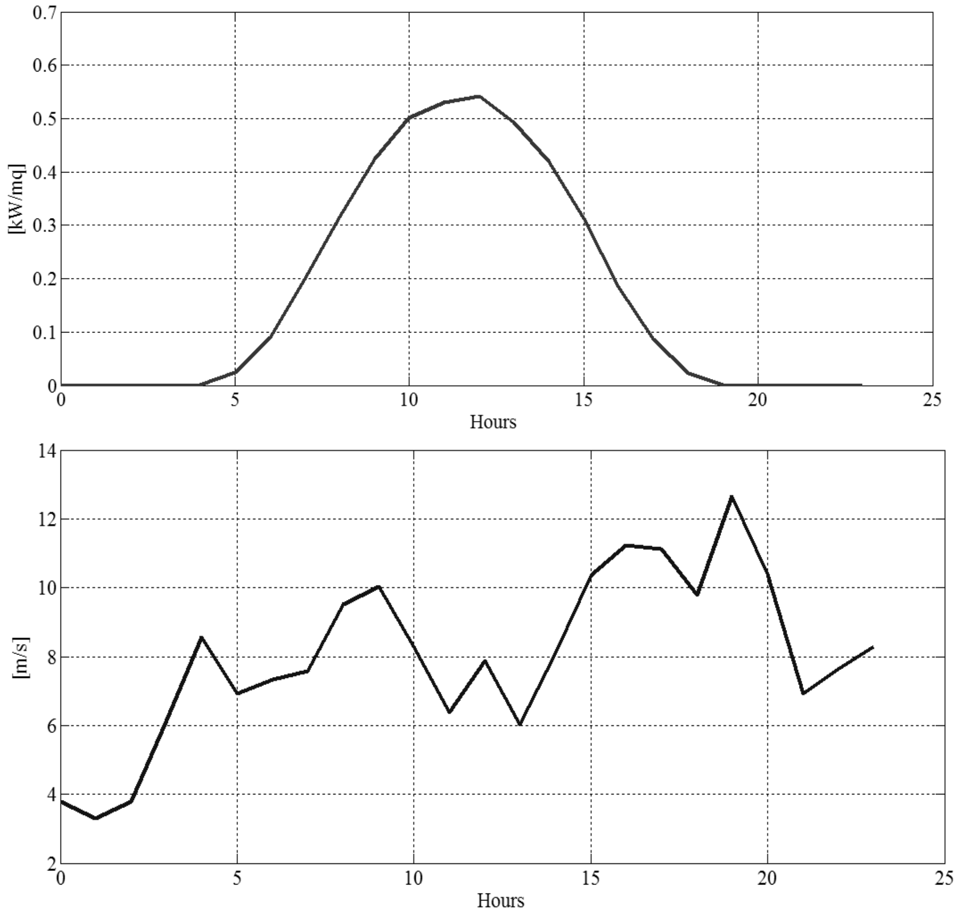


Figure 5.3 - Typical daily profiles of wind speed (down) and solar irradiation(up).

A set of three residential loads will be considered in this work, each one featuring the profile drawn in Figure 5.4.

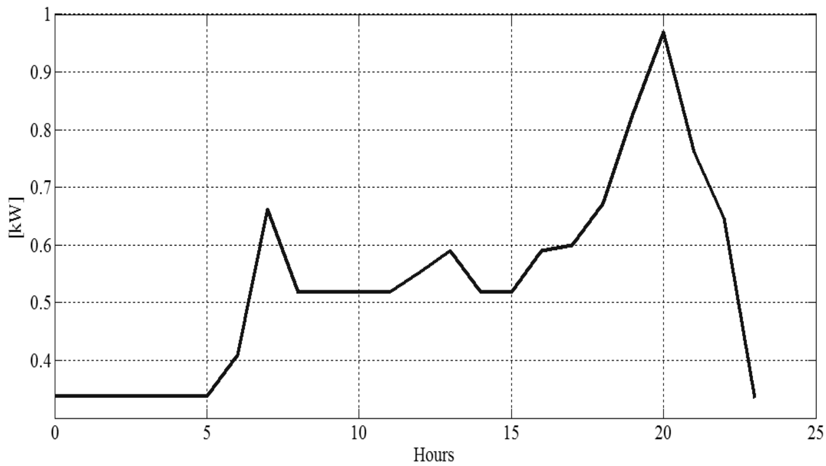


Figure 5.4 - Typical daily profile of a residential load.

5.2.2 Energy storage system

Wind turbines and PV array alone are fairly unable to track the power demand, leading to the introduction of suitable energy storage systems. Among different possible alternatives Lead Acid, Lithium-ion and Vanadium Redox Batteries are here considered.

A simple mathematical model of the ESS is considered in the proposed procedure to compute the State Of Charge (SOC), according to eq. (5.3):

$$SOC\% = \frac{E_0 + \int_0^T \left(\eta_C P_{in}(t) - \frac{1}{\eta_D} P_{out}(t) \right) dt}{E_{rat}} 100 \tag{5.3}$$

where: E_0 is the energy initially stored in the ESS, E_{rat} the ESS rated energy, E_{in} the input energy, E_{out} the energy delivered to the grid, η_C the charge efficiency and η_D the discharge efficiency.

5.3 LPSP index analysis

A Loss of Power Supply (LPS) occurs when the power delivered by the hybrid generator to the grid is not sufficient to fulfill the power demand. The LPSP index analysis is a useful tool to determine the probability that a LPS occur.

The total energy generated by the PV array and the wind turbine in the *k-th* interval is first evaluated by eqs. 5.1 and 5.2, on the basis of statistical wind speed and solar irradiation data. The generated power is then compared with the load energy demand. If the generated energy is larger than the load demand, the excess energy is stored into the ESS, taking into account the charge efficiency. If the generated energy is insufficient to supply the loads, some of the energy contained in the storage system is delivered to the grid. If the composition between the energy generated along the *k-th* interval and the energy stored in the ESS is not sufficient to support the load, a Loss of the Power Supply is detected, and evaluated through eq. (5.4).

$$LPS(k) = E_{Load}(k) - \left[E_{PV}(k) + E_{Turb}(k) + E_{ESS}(k-1)\eta_{ESS} \right] \eta_{SPC} \tag{5.4}$$

where: $E_{Load}(k)$, $E_{PV}(k)$ and $E_{Turb}(k)$ respectively represent the energy drawn by the load and the energy generated by the PV array and wind the turbine; η_{ESS} is the ESS round-trip efficiency and η_{SPC} is the global efficiency of the static power converters. Moreover, $E_{ESS}(k)$, the energy delivered or stored in the ESS is zero if the state of charge, obtained from eq. 5.3, is respectively higher than 100%, or lower than a minimum depending from the specific ESS technology. Finally, $E_{ESS}(k)$ must be lower or equal to $P_{rat}\Delta t$, being P_{rat} the rated power of the ESS.

The Loss of Power Supply Probability (LPSP) index is calculated over the entire T as:

$$LPSP = \sum_{k=1}^{N} LPS(k) \Big/ \sum_{k=1}^{N} E_{Load}(k) \tag{5.5}$$

The LPSP index ranges between 1 and 0, moreover a 0.0027 LPSP is normally considered acceptable, roughly corresponding to a loss of power supply of a day along one year of operations.

5.4 Hybrid generation system sizing

A sustainable energy balance is obtained if the energy generated along a day by WT and PV is greater or equal than the load demand.

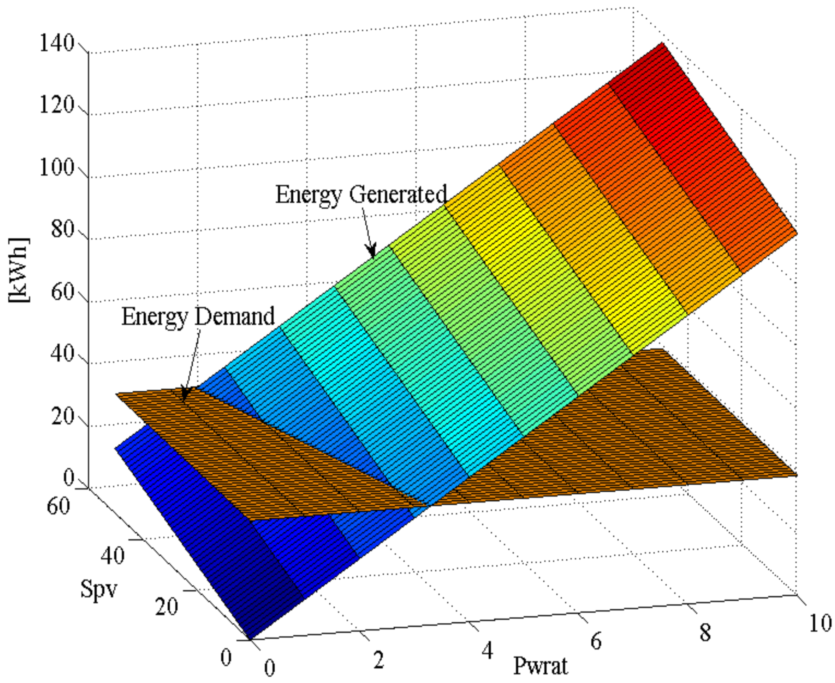


Figure 5.5 – Energy demand and energy generated vs. P_{Wrat} and S_{PV}.

The combinations of rated power of wind turbine generator PWrat and area of the PV array SPV able to satisfy such a condition, can be identified by comparison between the daily average energy demand and the produced energy, as shown in Figure 5.5.

Combinations of P_{Wrat} and S_{PV} which ensure the correct energy balance are potential solutions for the optimization problem. They are represented by points above the horizontal plane of the load energy demand. Three residential loads as that shown in Figure 5.4 have been considered in this case.

The cost of all the potential solutions is then computed, as shown in Figure 5.7. A 700€/m^2 cost for the PV plant and a 3000 €/kW cost for the wind turbine generator is assumed including the cost of power converters.

Any of the potential solutions requires a suitable storage device to meet supply continuity requirements. A loss of power supply index analysis is then performed to determine the lowest ESS size ensuring a 0.0027 LPSP. Such an analysis is accomplished for any of the potential solutions and for the three energy storage technologies considered.

The cost of the storage system and the whole hybrid generation system cost are then evaluated. Unit costs of ESS based on the three considered topologies are shown in Figures 5.8. and 5.9. Costs of LAB and Li-ion ESS only depend from the rated energy. Differently, the cost of a VRB-ESS is a combination of two factors, as such an energy storage system can be independently scaled on power and energy.

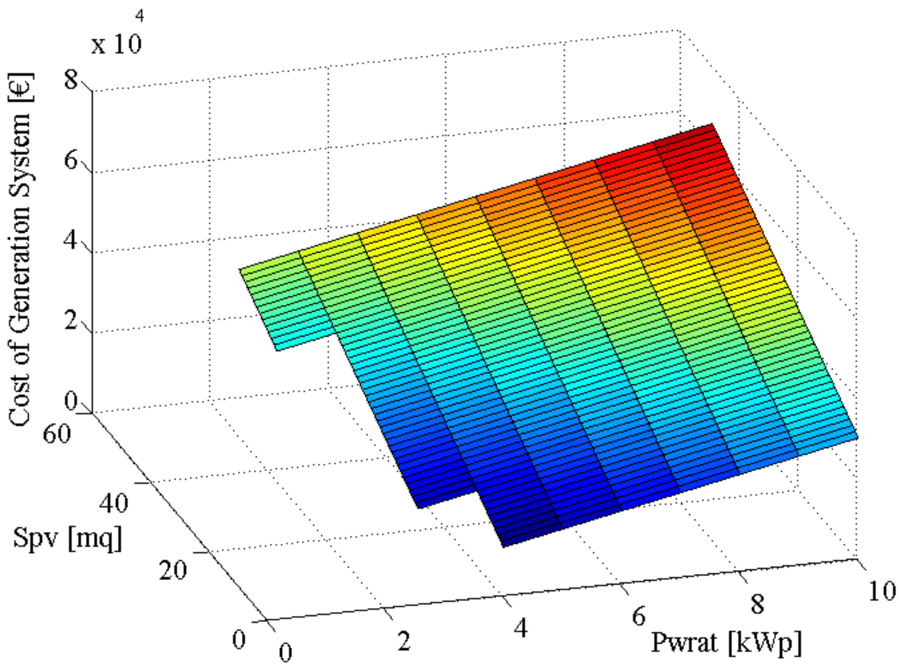


Figure 5.7 – Cost of WT and PV arrays for all the potential solutions.

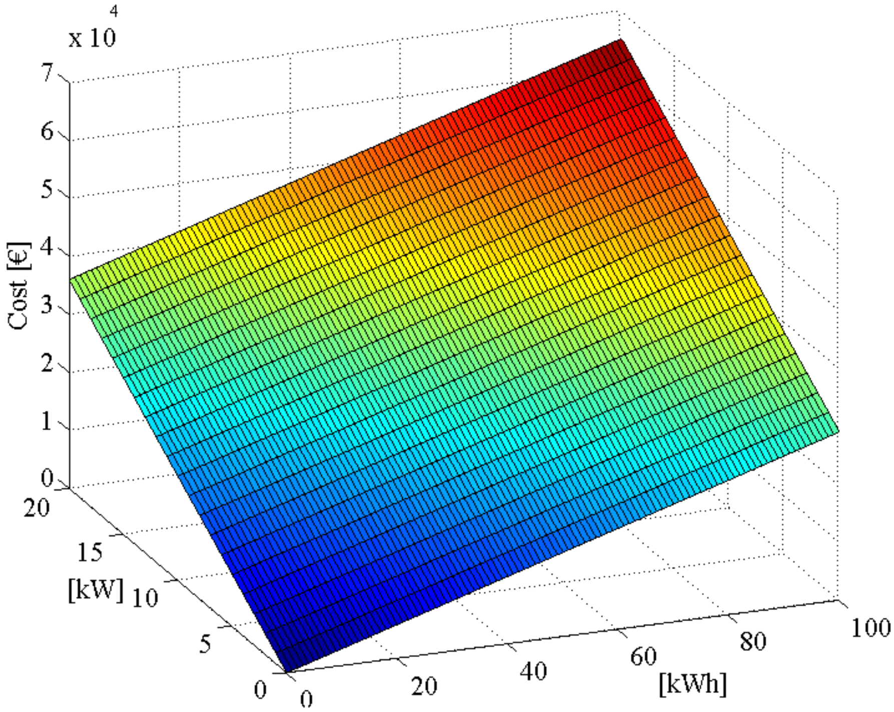


Figure 5.8 – Cost of VRB

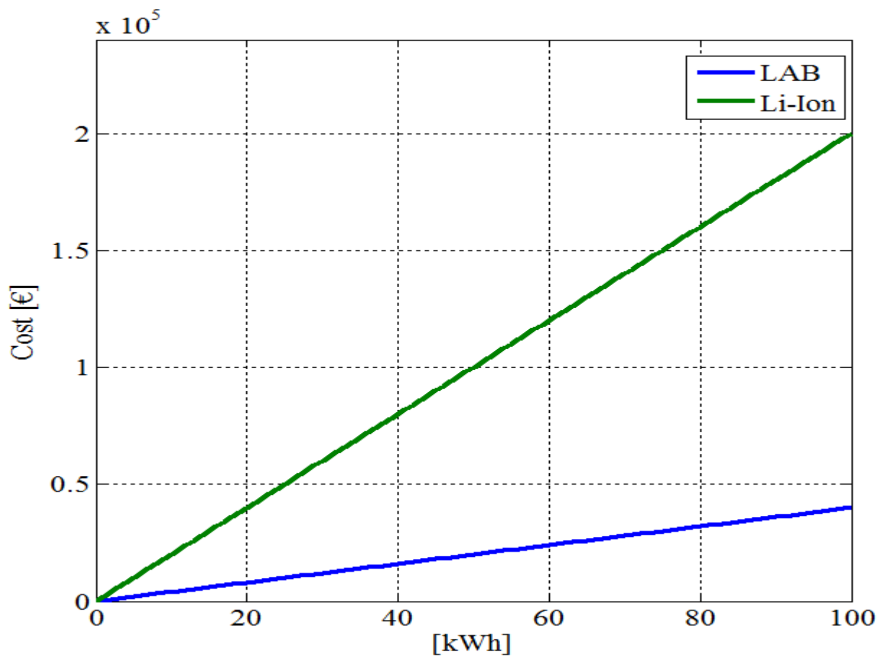


Figure 5.9 –LAB and Li-ion (down) ESSs.

Rated power and energy of the smallest VRB-ESS giving the target LPSP index for any of the potential solutions previously identified are shown in Figure 5.10. The cost of the whole hybrid generation system is then obtained by adding the cost of the VRB-ESS shown in Figure 5.11 to the cost of WT and PV generators, as represented in Figure 5.12. The minimum cost is reached by a system with only a single 4 kWp wind turbine and a 1kW, 13 kWh VRB-ESS, with a total cost of 17570 €. The same kind of analysis has been also accomplished on LAB and Li-ion energy storage systems, as shown in Figures. 5.13- 5.18. The optimal solution in the first case is a 4 kWp wind turbine complemented by 17 kWh LAB-ESS. The total cost is 18800 €. In the second case the optimal solution is a 4 kWp wind turbine with a 5 kWh Lion-ion-ESS, costing 22000 €.

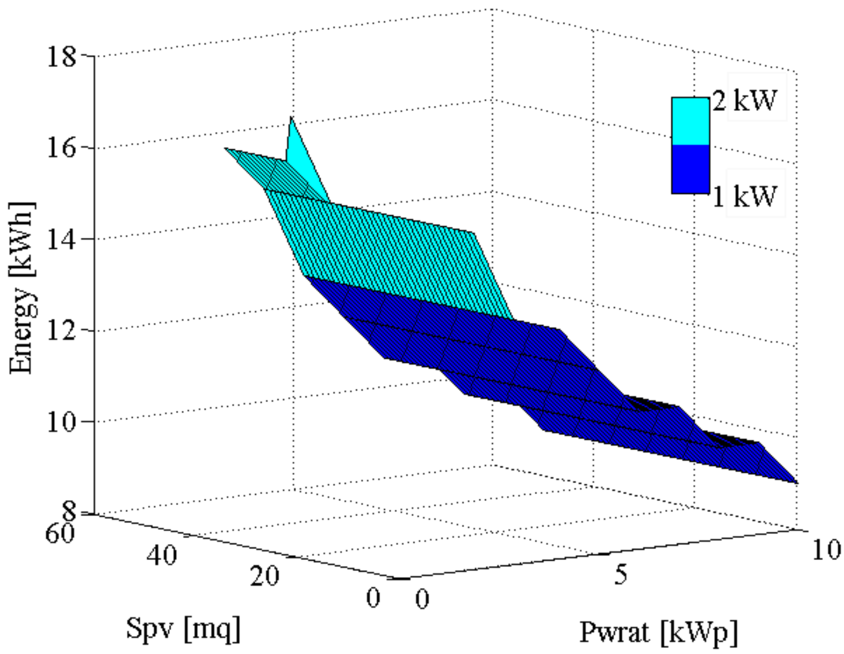


Figure 5.10 - VRB-ESS size vs. P_{Wrat} and S_{PV}

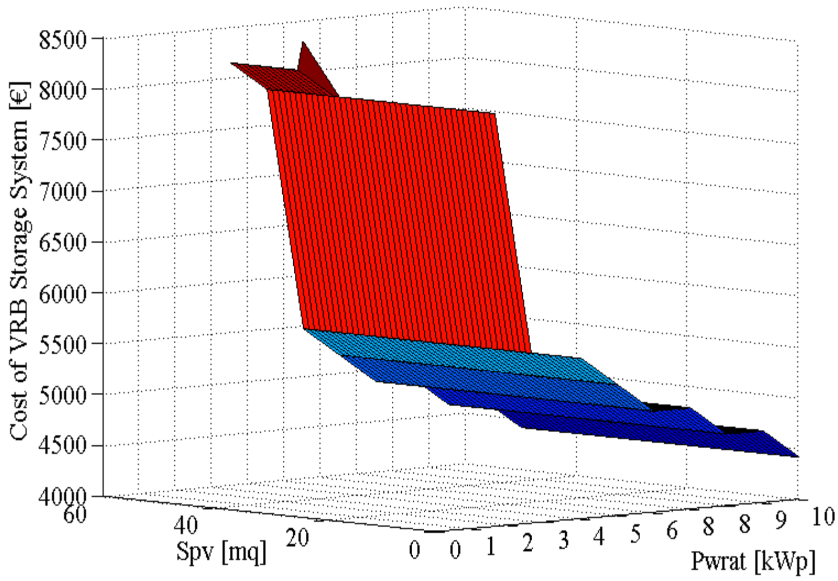


Figure 5.11 - VRB-ESS cost vs. P_{Wrat} and S_{PV}

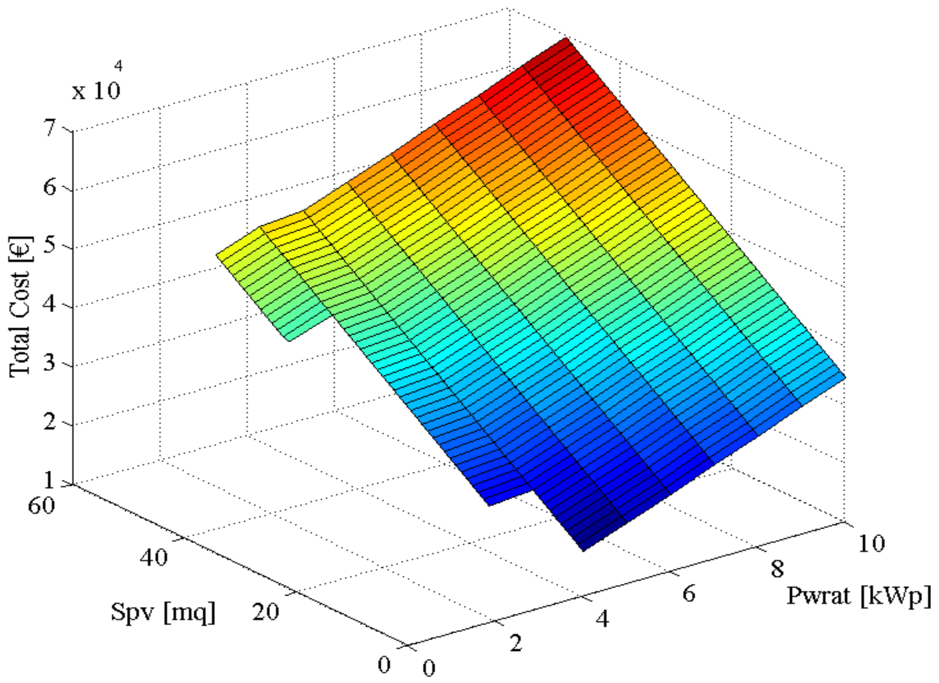


Figure 5.12 – VRB-ESS: total generation system cost vs. P_{Wrat} and S_{PV}

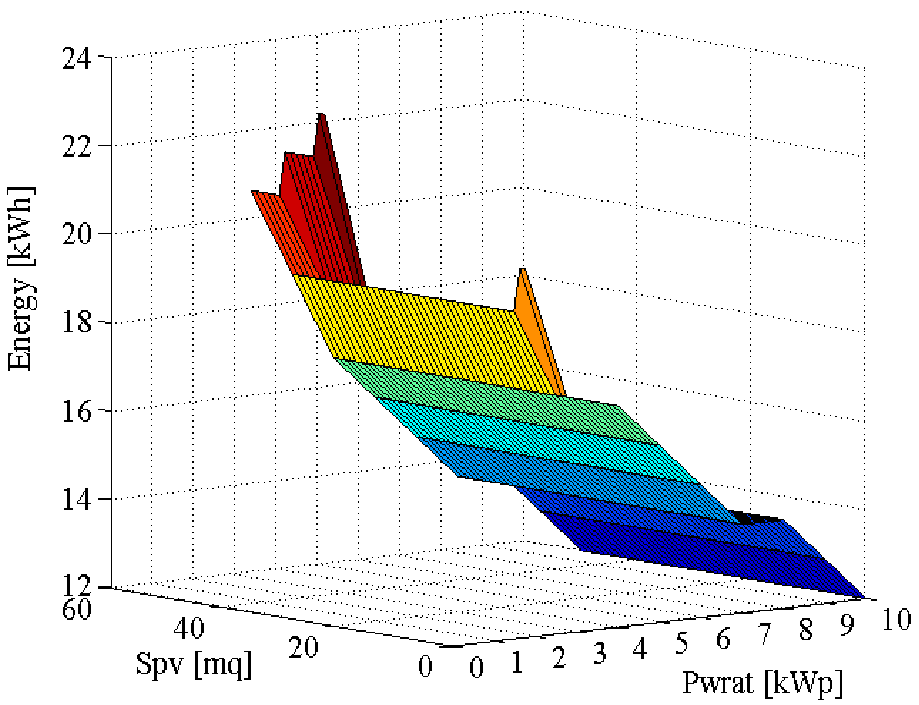


Figure 5.13- LAB-ESS size vs. P_{Wrat} and S_{PV}

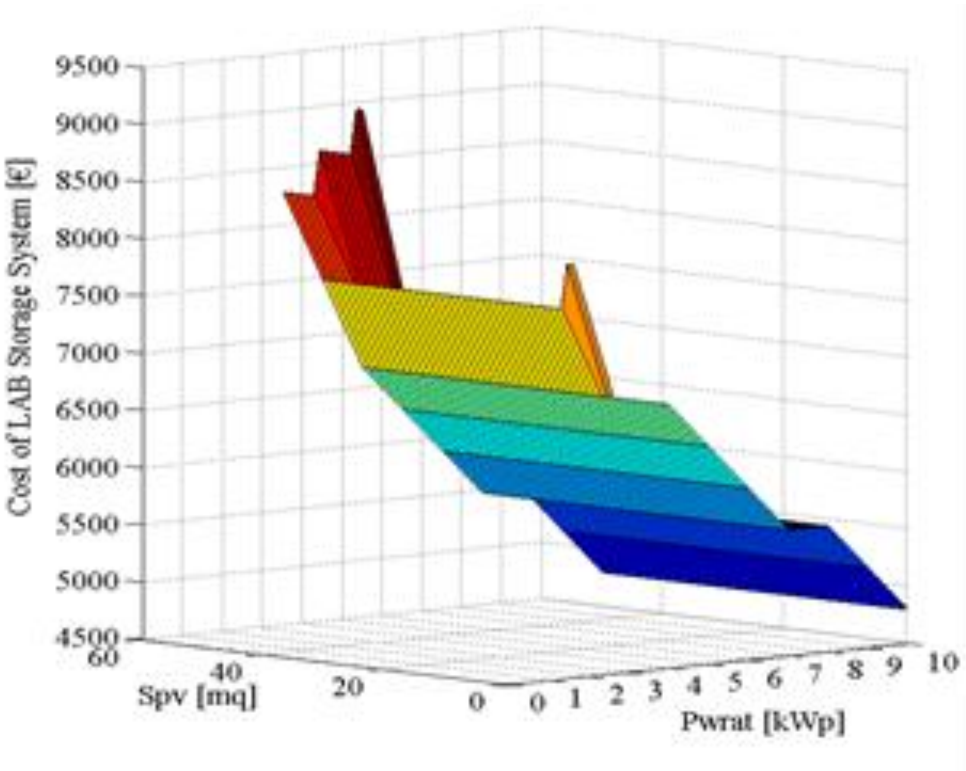


Figure 5.14 - LAB-ESS cost vs. PWrat and SPV

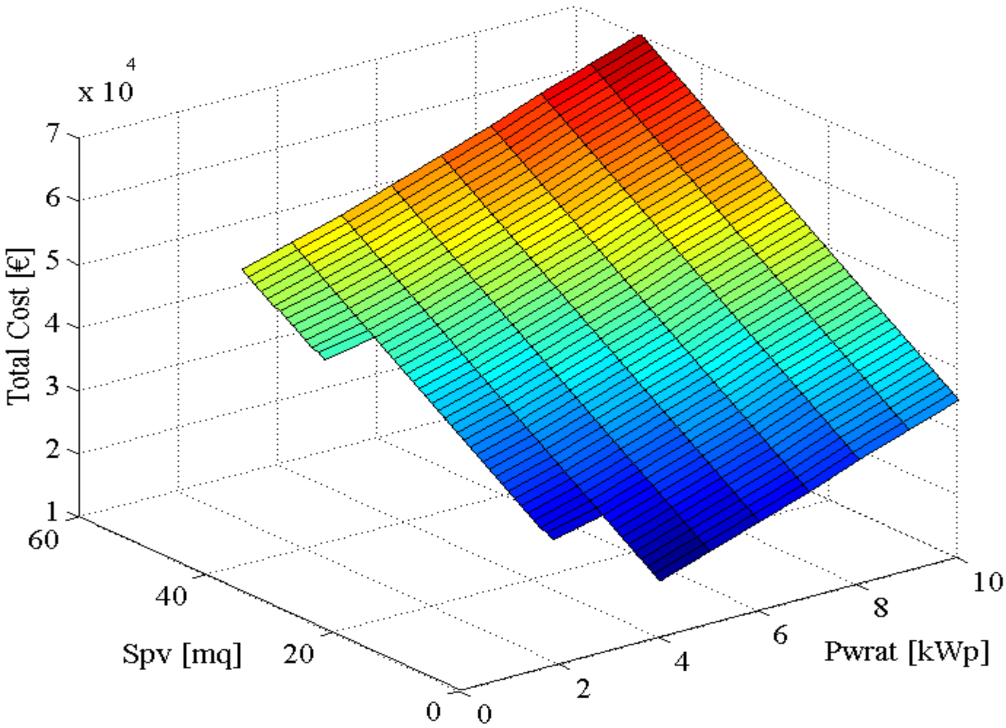


Figure 5.15- LAB-ESS total generation system cost vs. PWrat and SPV

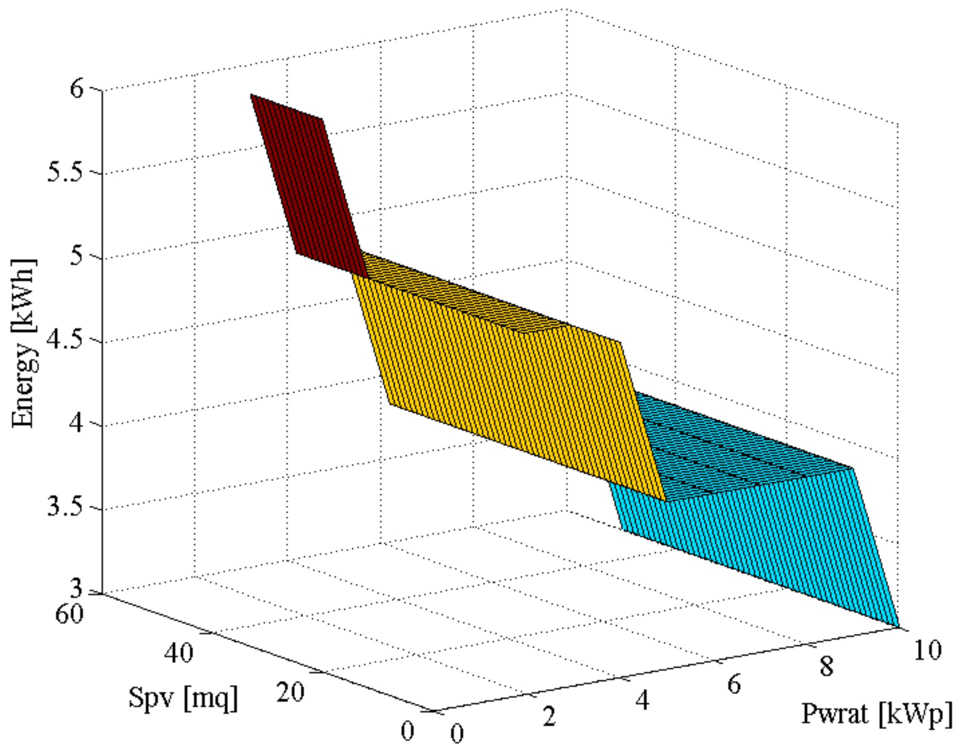


Figure 5.16– Li-ion-ESS size vs. PWrat and SPV

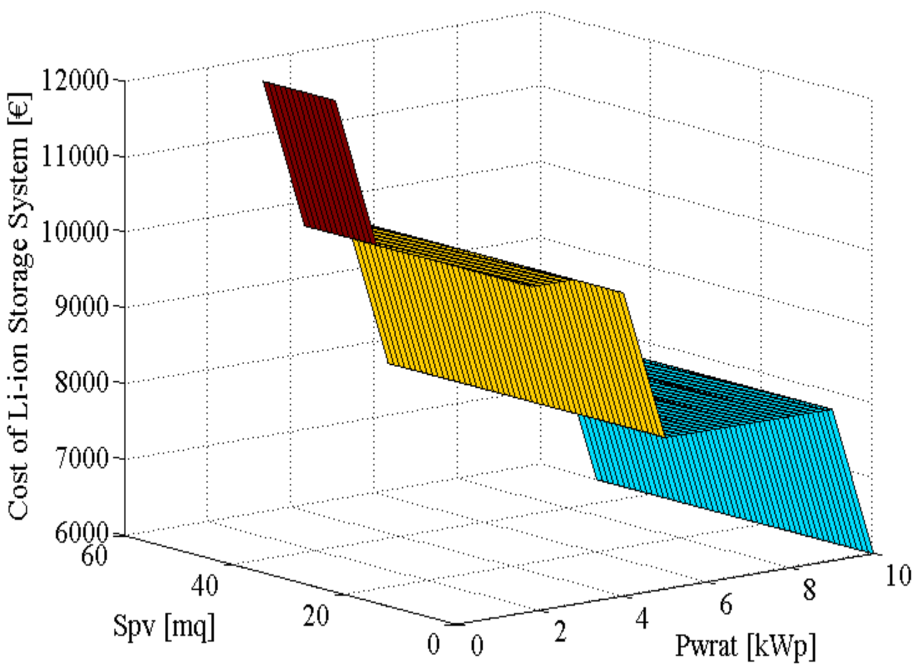


Figure 5.17 – Li-ion-ESS cost vs. PWrat and SPV

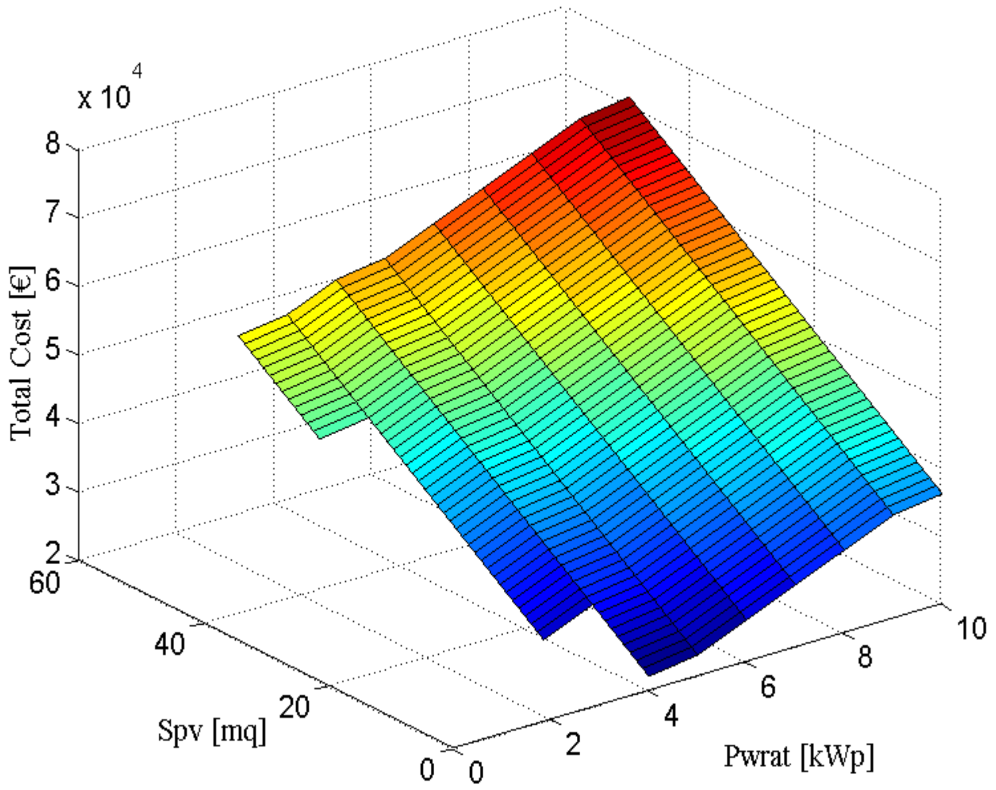


Figure 5.18- Li-ion-ESS total generation system cost vs. PWrat and SPV

5.5 Cost Analysis

The results obtained in the last section provide the ground for an accurate cost comparison among the best configurations obtained with the three considered energy storage technologies, on the basis of some key parameters, as presented in Table 5.I.

A first economic assessment can be accomplished through the ACC (Annual Capital Cost), which is computed as follows:

$$ACC = C_{init} CRF_{20} + C_{rep} CRF_{lt} \qquad (5.6)$$

being: C_{init} the capital and installation costs, C_{rep} the replacement cost. Moreover, CRF_{lt} is the Capital Recovery Factor for the considered lifetime lt, which is defined as:

$$CRF = [i_r(1+i_r)^k]/[(1+i_r)^k - 1] \qquad (5.7)$$

where: i_r is the yearly interest rate, typically 3%, and k the total lifetime expressed in years. Another interesting parameter to consider is the COE (Cost of Energy), which appraises the equivalent cost of the energy for systems operated in island mode. The

COE is computed as follows:

$$COE = (ACC_{total} + AMC_{total}) / TED \qquad (5.8)$$

where: ACC_{total} is the sum of the Annual Capital Costs of all components of the system, AMC_{total} is the total maintenance cost and TED is the total energy demand in a year.

Finally, a typical parameter to take into account when analyzing the economical convenience of island mode operated generation systems is the Break Even Line Extension Distance (BELED). It is defined as:

$$BELED = (ACC_{total} - COE_{GRID} TED)/(C_{CAB} CRF_{20}) \quad (5.9)$$

where: COE_{grid} is the cost of the energy drawn from the utility grid and C_{CAB} is the installation cost of an hypothetic power line connecting the loads to the utility network. A 20 €/m C_{CAB} is here assumed.

According to Table 5.I the most advantageous configuration is that equipped with a VRB-ESS, either in terms of ACC, either in terms of COE and BELED.

Table 5.I – Costs comparison

	Wind Turbine	**LAB ESS**	**VRB ESS**	**Li-ion B ESS**
Capital Cost *[€]*	*12000*	*6800*	*5570*	*10000*
Replacement *[€]*	*0*	*6800*	*1392.5*	*10000*
Installation *[€]*	*2400*	*1360*	*1114*	*2000*
Maintenance *[€]*	*200*	*0*	*100*	*0*
ACC_{total} *[€]*		*4347.9*	*1063.5*	*1861.44*
AMC_{total} *[€]*		*200*	*300*	*200*
COE *[€]*		*0.9968*	*0.2988*	*0.45182*
BELED *[m]*		*2623.3*	*180.22*	*773.769*

5.6 Conclusions

Hybrid Wind/Photovoltaic generators including energy storage devices have been proposed to improve the reliability of electric power generation in stand-alone operations. An optimal design of sophisticated systems including photovoltaic cells, wind turbines and energy storage devices is a quite complex task, which hardly can be accomplished by conventional tools. A probabilistic approach has been then proposed, based on the LPSP index, able to detect the most advantageous configuration, taking also into account the features of different energy storage technologies.

The proposed approach has been successfully exploited to design a hybrid generation system for a small set of residential loads, on the basis of wind speed and solar irradiation data.

Chapter 6

Sizing and stability assessment of grid connected large photovoltaic plants including energy storage systems

6.1 Introduction

Large photovoltaic (PV) generation plants are today rapidly spreading all over the industrialized countries, as a result of specific governmental policies, powered by strong climate concerns. As shown in Figure 6.1, in a traditional PV plant a large number of PV modules are series connected in long strings and a single centralized inverter provides the voltage inversion. Moreover, on large plants, a step-up transformer is required to boost the 480÷690 V inverter output voltage to the 13.8÷46 kV of the medium voltage utility network. The string architecture is however burdened by a low efficiency. Therefore, more sophisticated architectures have been developed where PV modules are arranged in strings, or even sub-strings, each one connected to the step-up transformer through a dedicated inverter, or a dedicated DC/DC converter and a centralized inverter.

Conventional distribution transformers are widely used, either singly or paralleled, to connect the inverter to the main power line. The step-up transformer and the inverter are two key element of a PV system, as they process the whole generated energy. Moreover, not only the efficiency and the cost are of primary concern, but also the influence of the power conversion system either on the amount of energy delivered to the main utility, either on the stability of the network. In fact, while selecting a rated power close to the PV plant peak power makes theoretically possible to fully transfer the captured solar energy to the utility network, such a design criterion will in practice lead to oversize both the transformer, the inverter and the power line [26],[27],[28]. Moreover, a too large transformer would operate for long times at a reduced efficiency, while generating a largely unpredictable power injection on the main grid. The last may lead to grid instabilities, causing frequent plant shutdowns, and requiring a remarkable reserve power to be provided by conventional generators. On the other hand, a too small step-up transformer would constitute a bottleneck, preventing an optimal exploitation of the solar energy.

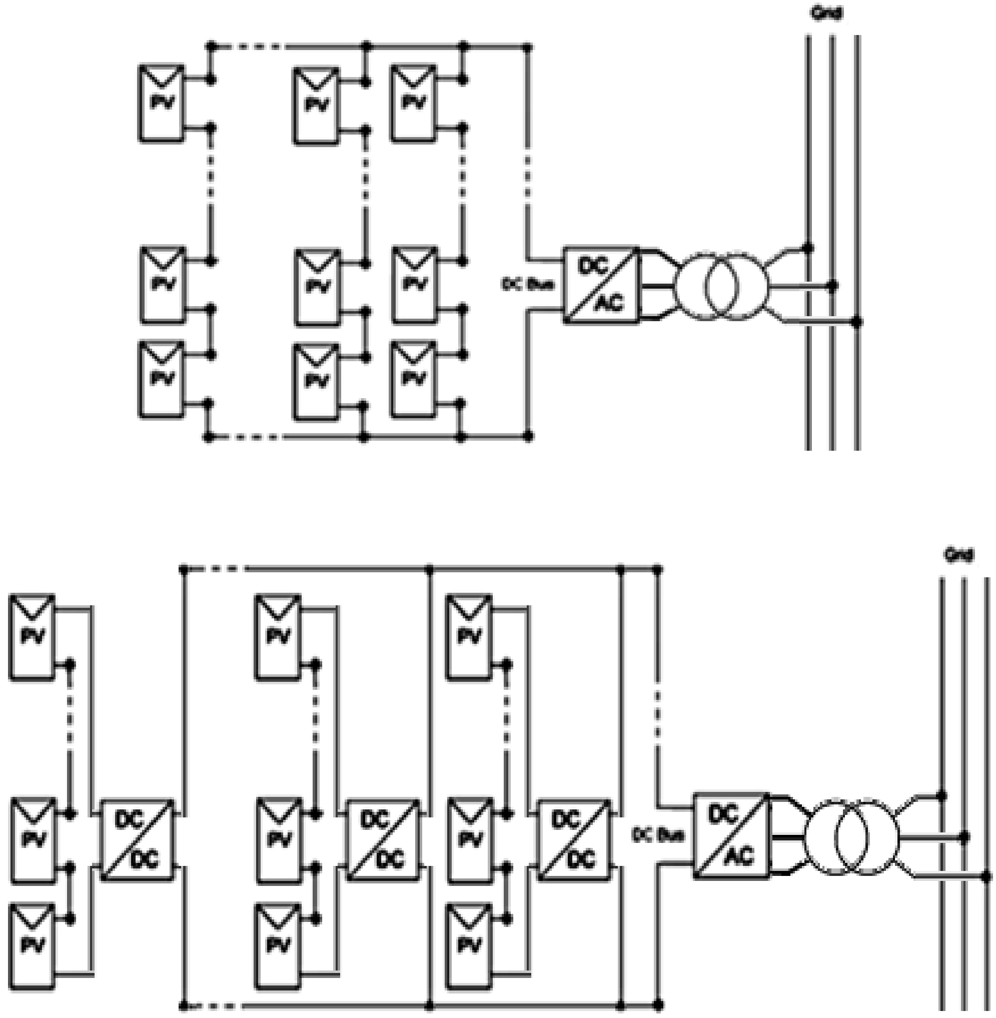


Figure 6.1 - String arranged (up) and decentralized (down) PV arrays with centralized inverter.

A PV energy plant is quite unreliable, because of the stochastic nature of the solar irradiation [29],[30]. To allow such a plant to match the standard requirements for grid stability some forms of energy storage can be introduced.

The selection of the rated power of the conversion system is a very complex task when considering a PV plant with energy storage capabilities, as an optimal solution must be detected taking also into account the features and the cost of the Energy Storage System (ESS) and their effects on the cost and efficiency of the whole system [31].
In general, the selection of the power conversion system in a PV plant is a quite complex task as several variables depending on the transformer and inverter rated power must be taken into account as: initial cost of the system, energy losses due to transformer efficiency, energy storage system efficiency and possible plant disconnections due to network instability.

6.2 Power conversion system for conventional PV plants

Even conventional distribution transformers are widely used as step-up transformers for PV plants, their customer price can be hardly estimated. In fact, they often are custom built units with unlisted prices. Only considering commercial off the shelf transformers and neglecting taxes and marketing markups, the cost curve of Figure. 6.2 can be considered, as function of the rated power. Main contributions to the final cost are given from manufacturer selling price, shipping and installation costs. Moreover, as the size and the cost of the inverter serving the plant are also closely related to the transformer rated power, a specific cost function, shown in Figure 6.2, is assumed.

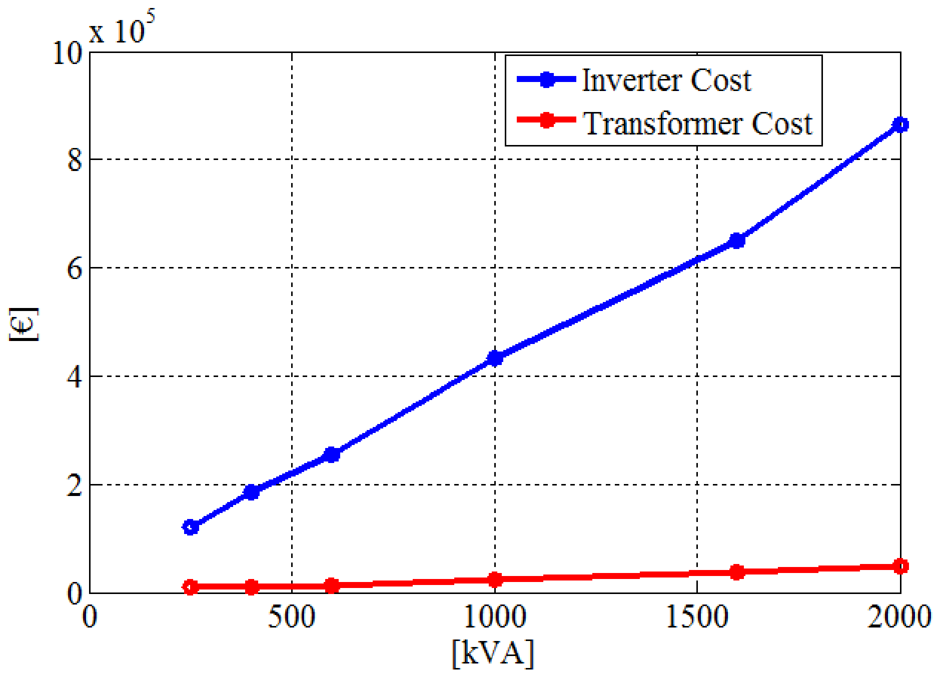


Figure 6.2 - Step-up transformer and inverter initial costs

6.2.1 Energy losses due to transformer overloads

Starting from an average daily solar irradiation profile, as that of Fig. 6.3, the input power P_i can be computed as:

$$P_i(t) = Irr(t)\ S\ \eta_{PV} \tag{6.1}$$

$$E_i = \int_0^T P_i(t)dt \tag{6.2}$$

where: S is the total net area of PV modules, $Irr(t)$ is the solar irradiation at time t and η_{PV} is the overall efficiency of PV panels and the power converters.

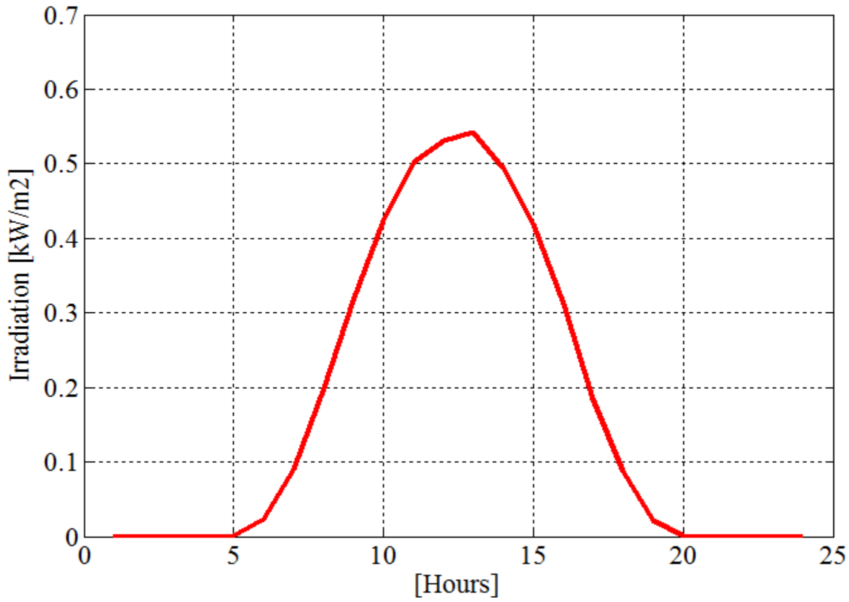


Figure 6.3 - Average daily solar irradiation in southern Europe

Depending on to the power conversion system rated power, some of the energy captured by PV modules cannot be delivered to the utility network. In order to evaluate the energy loss due to transformer overloads a probabilistic approach is followed based on the LPPP (Loss of Produced Power Probability) index. Such an approach derives from LPSP (Lost of Power Supply Probability) technique.

To accomplish the LPPP analysis over a given time window T the last is divided into N intervals, each one $\Delta t=T/N$ long. Typically, these intervals are taken to be of one hour duration. It is assumed that: if $P_i(k)$, the average input power during the *k-th* interval is greater than 110% the transformer rated power P_n, the excess power is lost, as it cannot be processed. For each *k-th* time interval, the LPP (Loss of Produced Power) parameter is computed according to Figure 6.4.

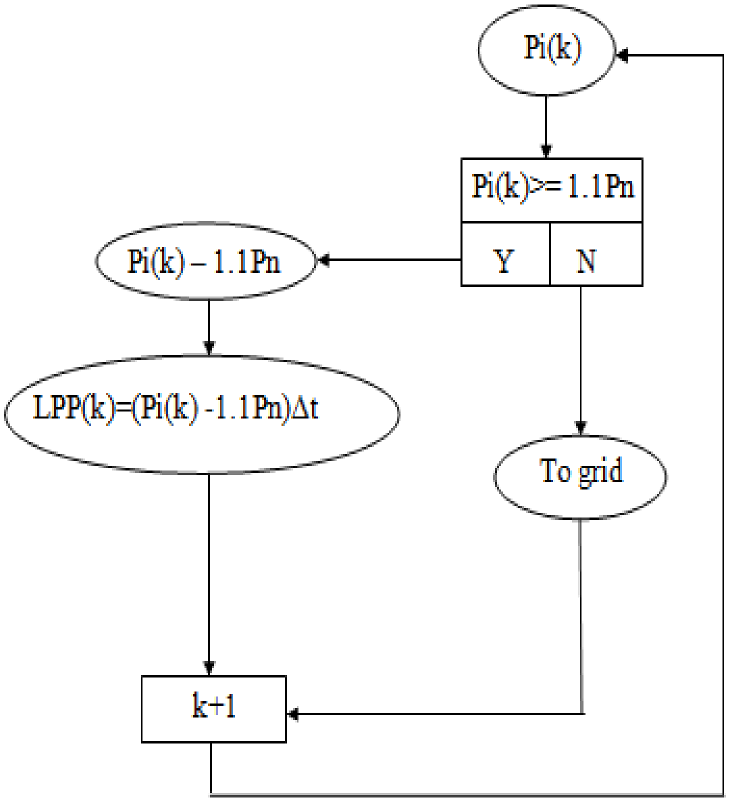


Figure 6.4 - Flowchart of the LPP algorithm

The value of the LPPP index is then determined as follows:

$$LPPP = \frac{\sum_{k=1}^{N} LPP(k)}{\sum_{k=1}^{N} Pi(k)\Delta t} \tag{6.3}$$

The LPPP index is zero when the maximum amount of the solar energy captured over a day by PV modules is effectively delivered to the utility grid. The lost energy and the associated cost are evaluated as follows:

$$E_W = \sum_{k=1}^{N} P_i(k)\ \Delta t\ LPP(k) \tag{6.4}$$

$$C_{EW} = E_W\ C_e \tag{6.5}$$

Being C_e the energy selling price per kWh.

6.2.2 Energy losses due to transformer efficiency

The power wasted due to no load and copper losses during the *k-th* interval can be computed through the following equation, assuming constant the amplitude of the inverter output voltage:

$$P_d(k) = P_v + \frac{P_c}{P_n^2} P_i^2(k) \tag{6.6}$$

where: P_v represents the no-load losses and P_c the rated copper losses.

The total energy wasted due to transformer power losses and the associated cost are then obtained as:

$$E_D = \sum_{k=1}^{N} P_d(k)\ \Delta t \tag{6.7}$$

$$C_{ED} = E_D\ C_e \tag{6.8}$$

6.2.3 Energy losses due to grid instability

The utility grid is forced to work around the point of balance between the power demand and the generated power [32],[33]. A suitable control system, in fact, manages the reserve conventional generation power to maintain the stability of the entire network. The solar irradiation is intermittent; moreover it often unpredictably varies according to the weather conditions. Therefore, the utility control system sees the power stream generated by a PV plant as a disturbance. The control system is able to compensate such a disturbance only until the delivered intermittent power represents a small share of the total power of conventional generators connected to the network. Such a share differs from country to country, but it ranges between 5 and 25%. Therefore, a large PV plant without energy storage is fairly subjected to frequent shutdowns to maintain the network stability, [34],[35],[36],[37]. This causes additional energy losses.

Energy losses caused by network instabilities can hardly be predicted in a general way. However, it is plain that they depend from PV plant peak power and the utility network stability margins [38], [39]. Assuming that an average shutdown consists of a four hours long full plant disconnection, centered on the peak of the solar irradiation, the energy lost due to grid instabilities and the associated cost can be computed as follows:

$$E_{lost} = P_{pk}\ N \tag{6.9}$$

$$C_{Elost} = E_{lost} \ C_e \tag{6.10}$$

being P_{pk} the peak output power of the plant and N the total time in hours per year in which the system is disconnected from the utility network for stability reasons.

6.2.4 Transformer size selection

Considering a *2MW* peak power PV plant, the transformers whose main data are summarized in Table 6.I have been selected for comparison. To simplify the comparison only single units are considered, working at unity power factor. However, the proposed approach can be easily generalized to transformer banks working at an arbitrary power factor. Estimating in 25 years the lifetime of the PV plant, total energy losses have been first computed as shown in Fig. 6.5.

TABLE 6. I –STEP-UP TRANSFORMERS MAIN DATA

Rated power [kVA]	***P_v [kW]***	***P_c [kW]***
250	*0.52*	*2.60*
400	*0.74*	*3.62*
600	*1.04*	*5.20*
1000	*1.3*	*8.97*
1600	*2*	*13.00*
2000	*2.4*	*16.08*

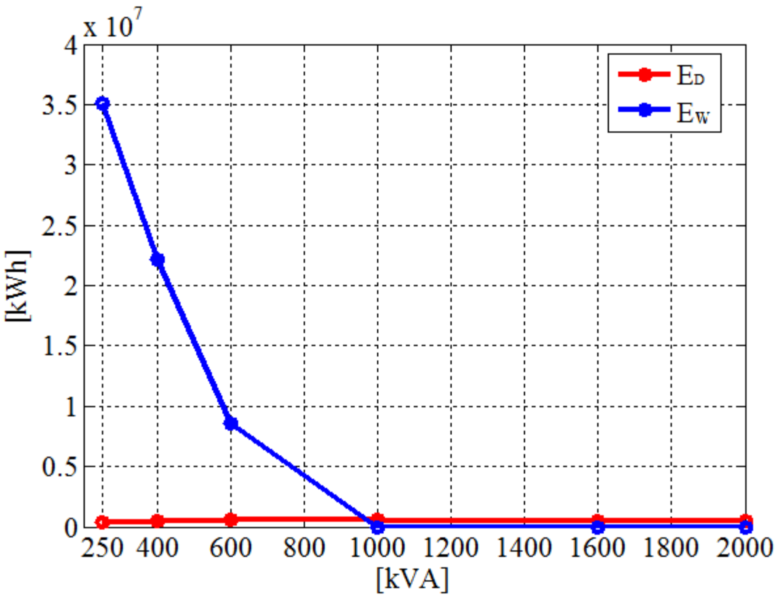


Fig 6.5 - E_D and E_W over 25 years vs. rated power.

Energy losses over 25 years due to grid stability have been also evaluated as shown in Figure 6.6 as function of *N*.

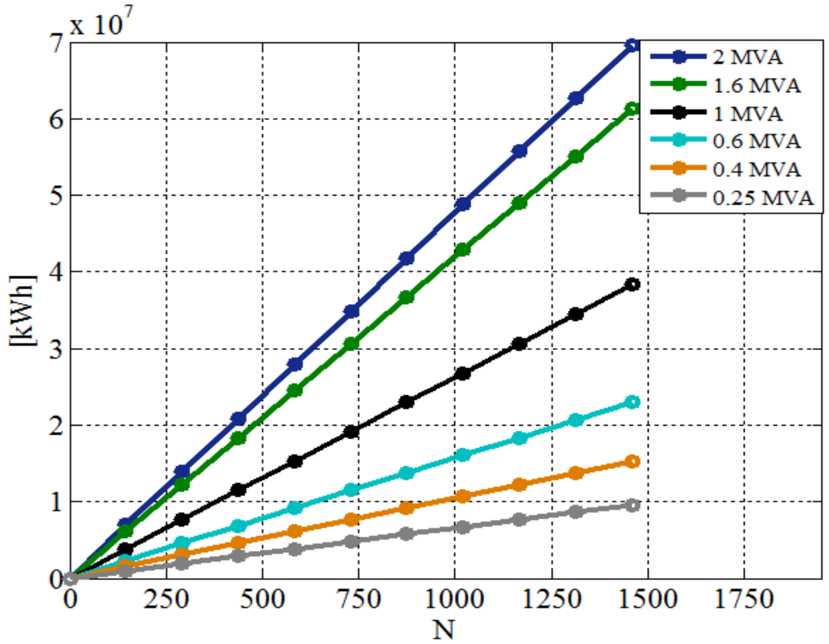


Fig 6.6 - E_{lost} over 25 years vs. expected hours of disconnection per year.

The cost of energy losses over 25 years has been then calculated and added to the initial cost of the transformer and the inverter. Taking also into account a 3% annual rate of interest, the life costs of the transformer and the inverter have been computed. Estimated life costs are then subtracted to the total price of the energy delivered to the main utility in 25 years. As shown in Fig. 8 the most advantageous transformer is that rated at 1 MVA.

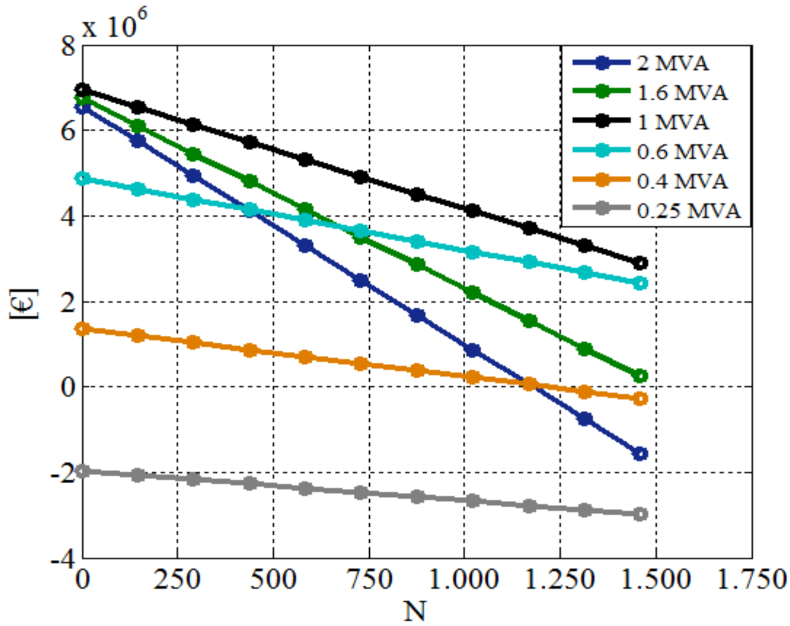


Fig 6.7 - Total life cost vs. expected hours of per year.

6.3 Transformers for PV plants with energy storage

In this case the cost of the energy storage system must be added to the cost of the transformer and of the inverter. A cost curve for large VRB ESS is shown in Figure 6.8.

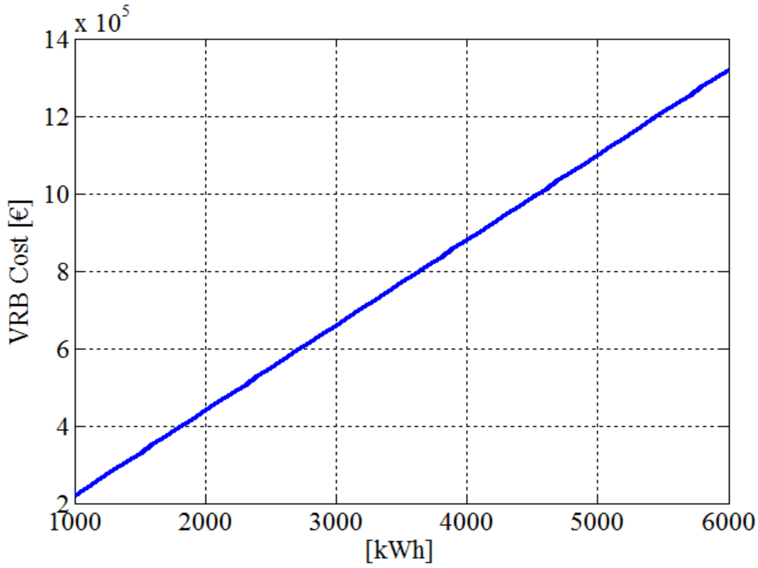


Figure 6.8 - .VRB Energy Storage System initial cost.

6.3.1 Energy losses due to transformer overloads

The LPP is computed for each *k-th* interval according to the flow-chart of Figure. 6.9. If $P_i(k)$ is larger than 110% the transformer rated power, the excess energy can be stored into the VRB ESS, taking into account conversion and charge efficiencies. However, if the state of charge of the ESS is nearly 100% the excess energy is lost. Moreover, if the excess power outreaches the VRB ESS maximum power P_{ESSMAX} the surplus energy is lost. If $P_i(k)$ is lower than the transformer rated power, some energy is drawn from the VRB ESS to keep the transformer at the maximum efficiency working point. Moreover, if $P_i(k)$ is greater than P_{ott} the input power corresponding to the maximum efficiency working point, all the power is delivered to the utility network. If not, some power is provided from the energy storage system.

The LPPP index, the lost energy and the associated cost can be evaluated according respectively to eqs. (6.3), (6.4) and (6.5).

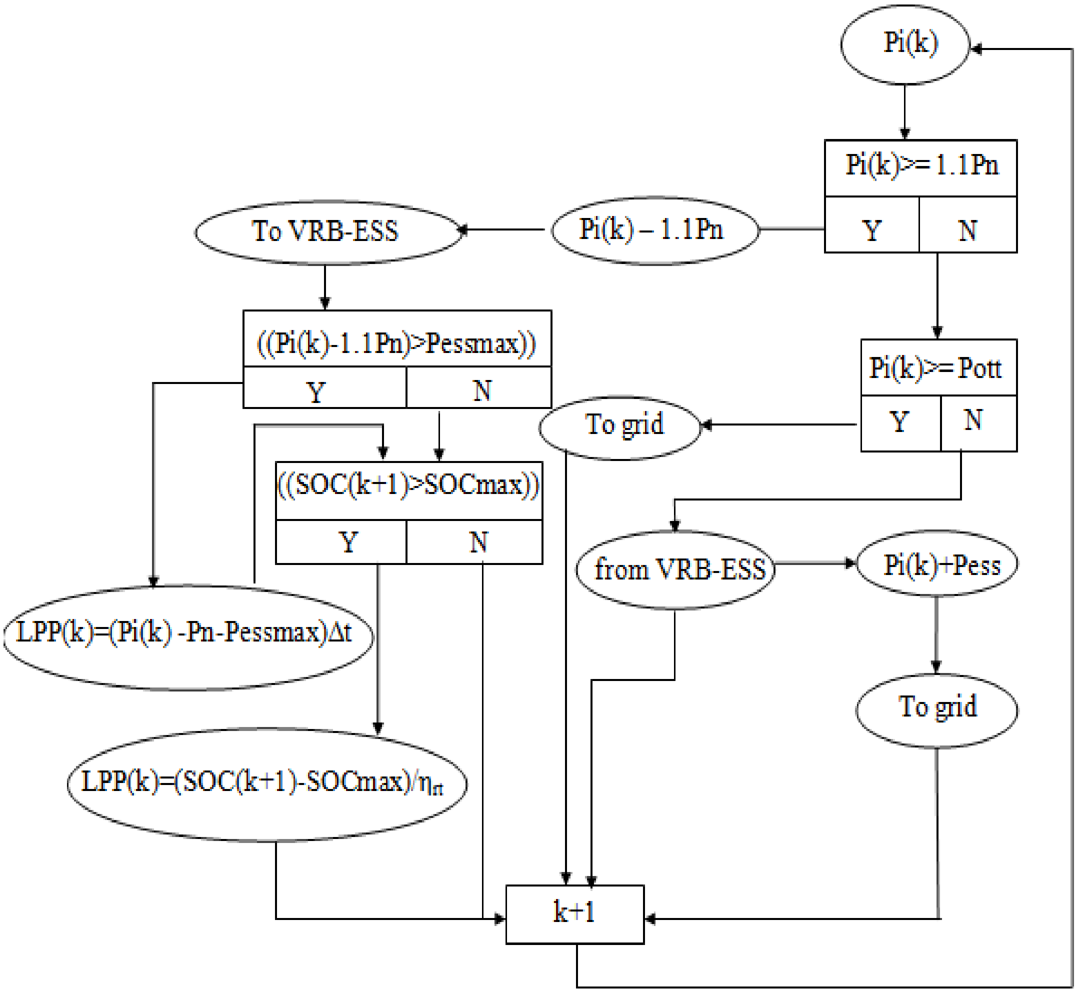


Figure 6.9 -.Flowchart of the LPP algorithm

6.3.2 Energy losses due to transformer efficiency and grid instability

The power wasted due transformer losses during the *k-th* interval can be computed through eq. (6.6), while associated lost energy and cost through eqs. (6.7) and (6.8) respectively.

A PV plant equipped with an energy storage system is able to modulate the power delivered to the network, leading to fewer shutdowns if compared with a PV plant featuring the same peak power but no energy storage. In order to compare PV plants with and without energy storage an equivalent total amount of hours per year in which the system is disconnected from the utility network is defined as:

$$N' = N\frac{\Delta P}{P_{pk}} \tag{6.11}$$

being ΔP the power variability, defined as the difference between P_{pk} and the minimum value of the power delivered to the utility network over a day (zero if no energy storage is provided). According to eq 6.11 the total length of network disconnections is quite conservatively considered proportional to the variability of the power generated by the PV plant. Therefore, without energy storage ΔP is equal to P_{pk}, giving $N'=N$. At the contrary, if a suitable energy storage system holds constant the power generated over a day, N' becomes zero. In fact, if the generated power is constant and fully predictable, no interference to the network stability may occur. Under the above mentioned hypotheses, the energy lost by a PV plant due to system instabilities, can be estimated as:

$$E_{lost} = P_{pk}N' = \Delta P\, N \quad (6.12)$$

Different hypotheses can be easily also considered, as partial disconnections, or average plant disconnections featuring different lengths.

Additional costs due to possible system shutdowns can be computed through eq. 6.10.

6.3.3 Transformer size selection

The 2 MW PV plant previously described is here considered including a VRB-ESS featuring a 75% round trip efficiency. Three different design approaches have been considered, namely:

1. A VRB ESS featuring the minimum size to ensure LPPP=0 (maximum solar energy delivered to the utility grid), while holding the transformer working at the rated power.
2. A VRB ESS able to ensure LPPP=0, while holding the transformer working at the maximum efficiency during the discharge of the energy storage system.
3. A VRB ESS able to ensure LPPP=0, while holding the transformer working at 99% of the maximum efficiency during the discharge of the energy storage system.

In any case the energy balance over a day must be nearly zero, to ensure that the final state of charge of the energy storage system is close to the initial value.

The first approach lead to the minimization of the transformer rated power. The second approach lead to the maximization of the average system efficiency. The third approach has been considered as an attempt to reduce the cost of the VRB ESS, only slightly lowering the average system efficiency.

A VRB ESS can be independently sized on storage capacity and power. Therefore the LPPP index analysis has been exploited to find the most advantageous combination among: transformer rated power, VRB ESS energy storage capability and VRB ESS maximum power, for the three approaches.

Considering the transformers whose data are shown in Table I, optimal solutions for the three considered approaches are reported in Table III. In Figure. 6.10 the LPPP index for different values of VRB ESS energy storage capability and maximum power is shown for the three selected solutions.

Design Approach	***Transformer [kVA]***	***VRB ESS [kWh]***	***VRB ESS [kW]***
1	*250*	*5200*	*675*
2	*400*	*3600*	*525*
3	*600*	*1800*	*325*

Results of some simulations dealing with the behavior of the three selected solution over a day are shown in Figures. 6.11 and 6.12. Specifically, the VRB ESS state of charge and the transformer efficiency over an average day, according to the three solutions are shown.

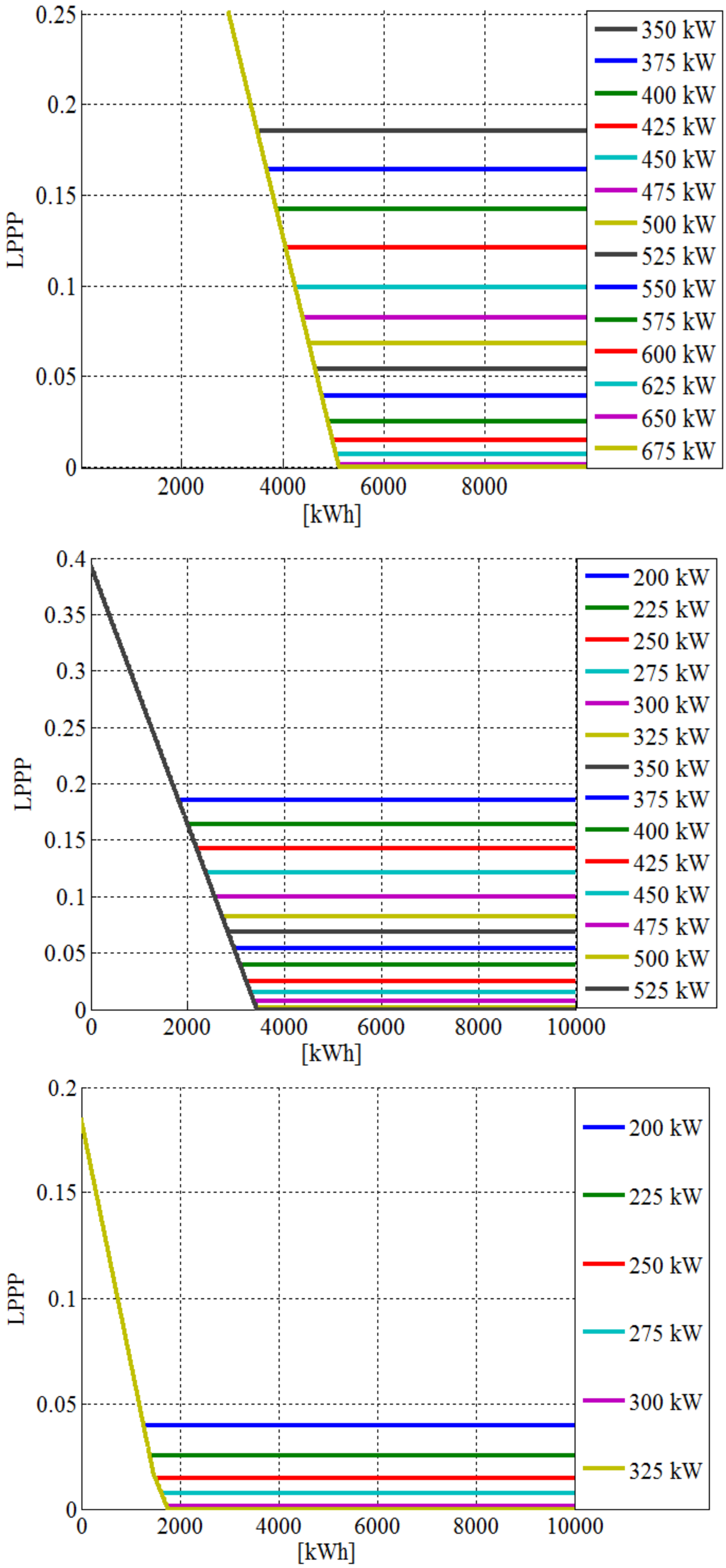


Figure 6.10 - From up to down the LPPP index for 250, 400, 600 kVA transformer.

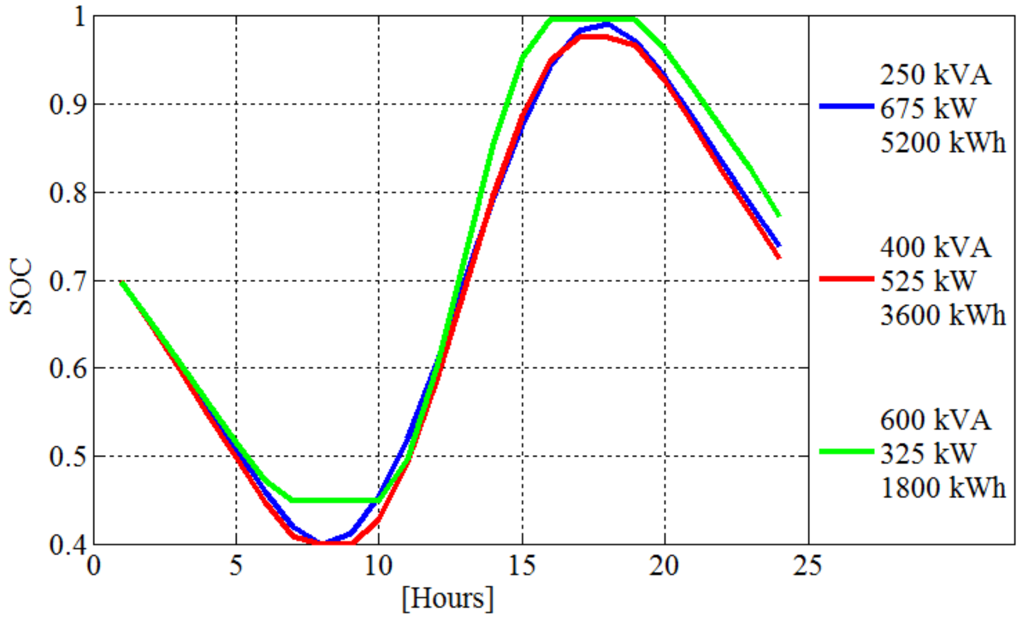


Figure 6.11 - VRB ESS state of charge over a day.

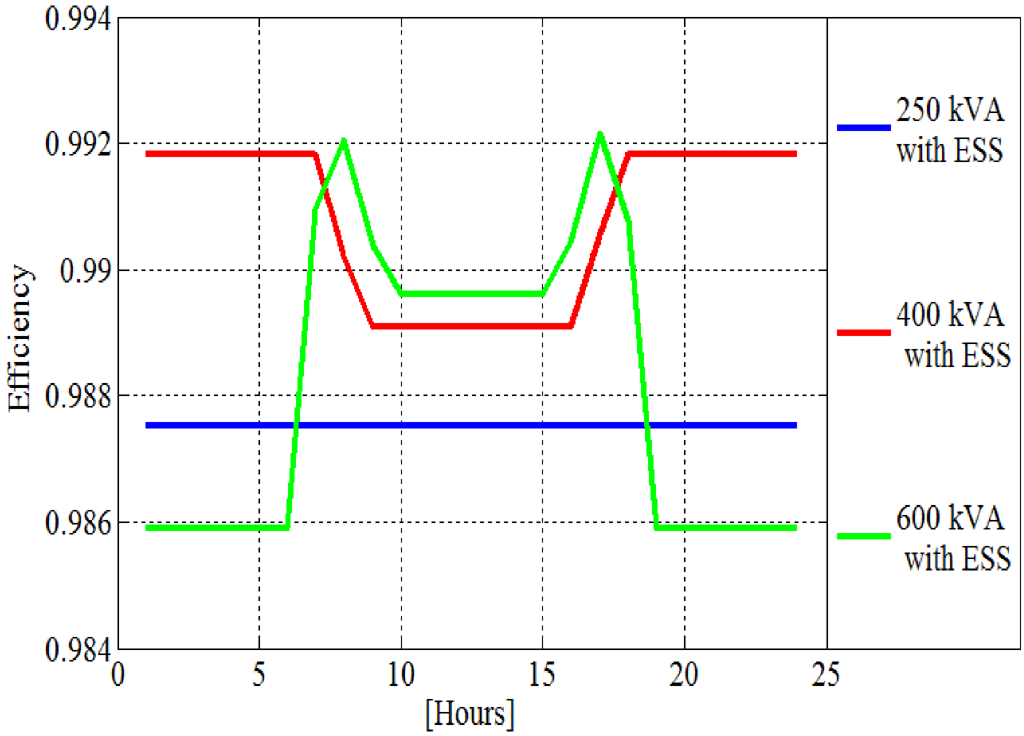


Figure 6.12 - Transformer efficiency over a day.

As in systems without energy storage, energy losses over 25 years due to grid stability have been computed, as shown in Fig. 6.13 for the three solutions and for different values of *N*.

The life cost of the three selected solutions has been computed also considering the initial cost of the energy storage system. Life costs have been then subtracted to the proceeds of the sale of energy over 25 years. Obtained results are shown in Figure. 6.14 and compared with the best solution obtained without energy storage.

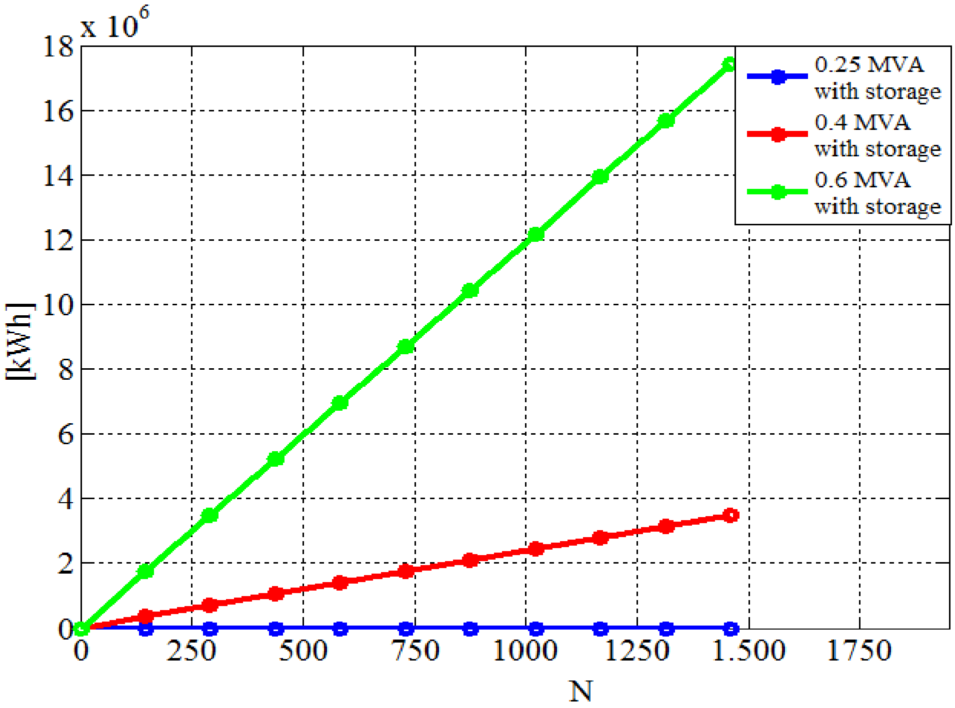


Figure 6.13. E_{lost} over 25 years vs. expected hours of disconnection per year.

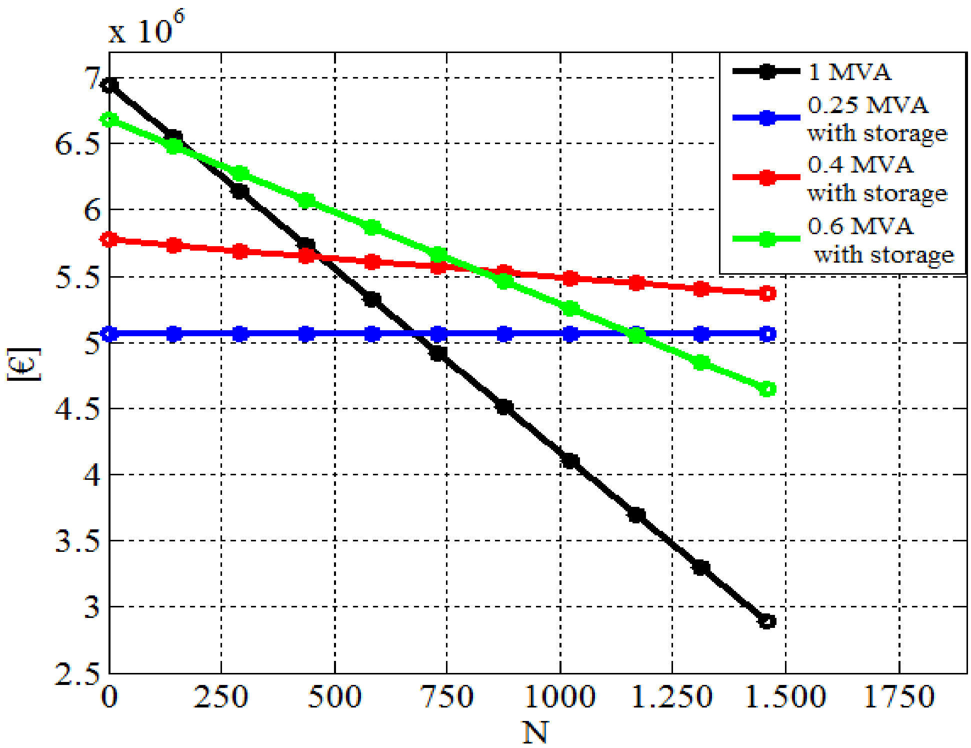


Fig 6.14 - Total life cost vs. expected hours of disconnection per year.

As it is possible to observe for very stable utility grids the most advantageous solution is indeed that without energy storage. However, decreasing the grid stability margins, PV plants with ESS perform better. Specifically, over an expected global duration of shutdowns larger than 140 hours per year, the PV plant with a 600 kVA transformer and a 1800 kWh VRB ESS is progressively more advantageous. Over 850 hours per year of expected plant shutdown, the most advantageous solution is that with a 400 kVA transformer and a 3600 kWh VRB-ESS.

6.4 Conclusions

A correct selection of size of the power conversion system in a PV plant involves a deep analysis of the whole system, as several variables are related to the power conversion system rated power as: initial cost of the system, energy losses due to transformer efficiency, energy storage system efficiency and the expected number of plant disconnections due to network instability.

The proposed approach is based on the evaluation of a probabilistic index the LPPP, to estimate the costs of energy losses related to the size of the transformer and the power and the storage capability of the ESS. Moreover, energy losses related to network instabilities are also considered. Taking into account full life costs optimal solutions can be detected according to the network power control capabilities.

Chapter 7
A VRB ESS for a large Turbogas Power Plant

7.1 Introduction

In this study the power production of a conventional 400 MW Turbogas Generator plant is considered. The Isab Energy Turbogas generating plant in Priolo has two main operating modes during the 24 hours. These operating modes are managed day by day by a production planning made by the Energy Management Group according to agreement with the GME (Gestore dei Mercati Energetici).

During daylight hours the TG plant generates an almost constant power, operating close to the point of maximum efficiency. During this period the price of energy sold to the Manager is maximum (with references to the day, or to the production plan drawn up by the day before market MGP) as this is the period of peak of energy demand by utilities. In this period (from about 7.00 to 22.00) the generation plant works in the best conditions being the machines near to the maximum point efficiency and thus having the maximum gain in accordance with the market demands.

On the contrary, from 22.00 to 7.00 am, the TG group needs to work at reduce-power, leading to a reduction in efficiency and in profit. In fact, approximately 280 MW of power produced at night. Among them, 80 MW are used for self-production, about 160 MW are sold according to special contractual conditions (bilateral agreements), while the remaining 40 MW are sold to the GME. However on the night hours the market price that, due to a poor energy demand, is very low, fluctuating between 20€/MWh and 0€/MWh.

A further reduction in the system operating rate at night, however, is difficult to achieve as it is economically disadvantageous. A reduction in the produced power means a lower efficiency of the TG group while a totally shut down of some machines means to be not able to respond in case of sudden failure caused by high start-up times.

A solution to this problem can be achieved through the inclusion of high-performance storage systems into the TG production system. With suitable storage systems, the energy produced at night can be stored to make it available during the peak demand hours. In this way, the 40 MW produced during the night and sold to the GME at very low price can be sold during daylight increasing revenues and reducing losses.

7.2 Day Before Market (MGP)

This market rules the relationships between producers and wholesalers participating in the economic negotiations. In this market the programs for injection and drawn of energy and the portion relating to transit capacity are defined. The MGP market is held on the morning of the day before the energy's delivery.

The formation of offer and demand is based on the energy exchange between the participants, buyers and producers. Each producer submits a proposal of sale. This proposal includes the quantity of energy that the producers want to enter into the market and the minimum selling price. Buyers submit their bids and set the maximum price. Offers to sell are selected in order to increase the price and purchase offers are selected in descending order of price. The marginal price system is the equilibrium price that is obtained by comparing the offers of sale and purchase, such as to maximize the volume of trade.

In the *Marginal Price System* all the operators are remunerated at the marginal price equal to the last offer selected, regardless of the price previously offered by each operator.

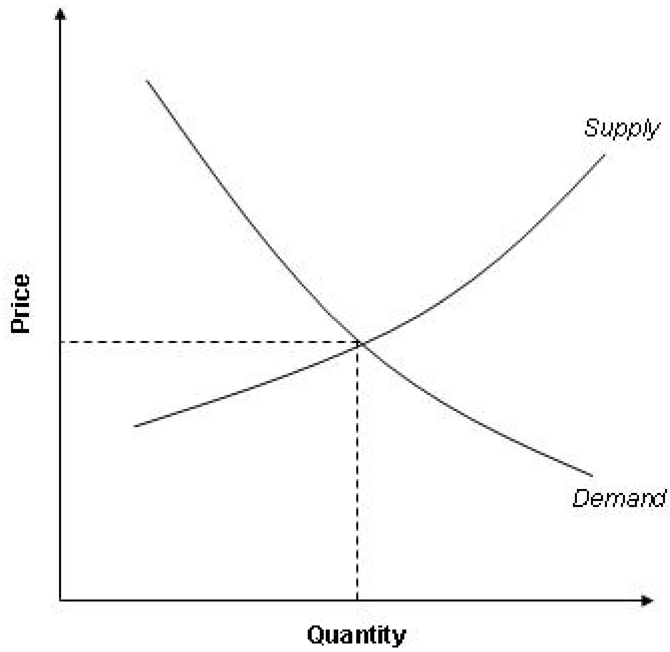


Figure 7.1 – Marginal Price System formation

7.3 Proposed Approach

For this analysis it has been considered the production plan of the last year. It is evident from the profiles that the production of the plant is subject to a high variability. However, this variability is due to production requirements, such as maintenance and / or reviews, and to the market requirement, which are notoriously subject to predictable variation. In this study the considered profiles correspond to a set of requirements related to the production.

In particular it is supposed to consider the overnight production constant and equal to the minimum technical plant (300 MW).

Figure 7.2 shows the average profile of production (blue) and the power supplied to the grid during the day (red). Usually this two profiles are coincident, but as part of this work, it will be considered as loads only the amount of energy subject to establishment constraints (required for self-coverage) and to the market (sold to the GME for contractual obligations). The remaining amount of energy produced is not covered by contractual obligations, but it is necessary for the proper operation of the plant. This amount is considered to be free of restrictions to the operator or other end users. This percentage is then available for other uses and, in particular with regard to this study, the storage.

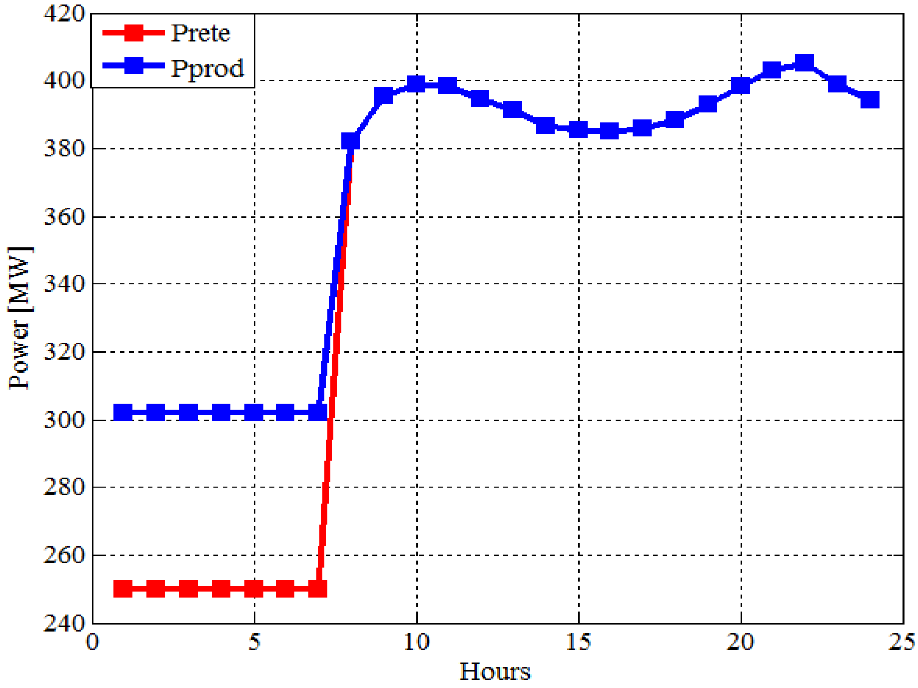


Figure 7.2 - Production profile (blue) and load profile to the grid(red).

It is only considered the possibility of using the energy stored during the night, or at least during the hours of low demand, to be sold the next day on the market.

The grid (including the amount for the self-production) is represented by a load curve which assumes a maximum during the hours of greatest demand (daytime) and a minimum, considered constant, during the night.

7.4 Simulations results

A set of simulations were conducted starting from the average profile shown blue in figure 7.2, and simulating the red profile as the load required. The simulations results show a range of possible sizes of the storage system that are able to retrieve a part of the whole amount of energy produced by the plant.

The used index is the LPPP introduced in chapter 6. This index aims to identify the percentage of reusable energy for the MGP according to different size of the VRB Energy storage system.

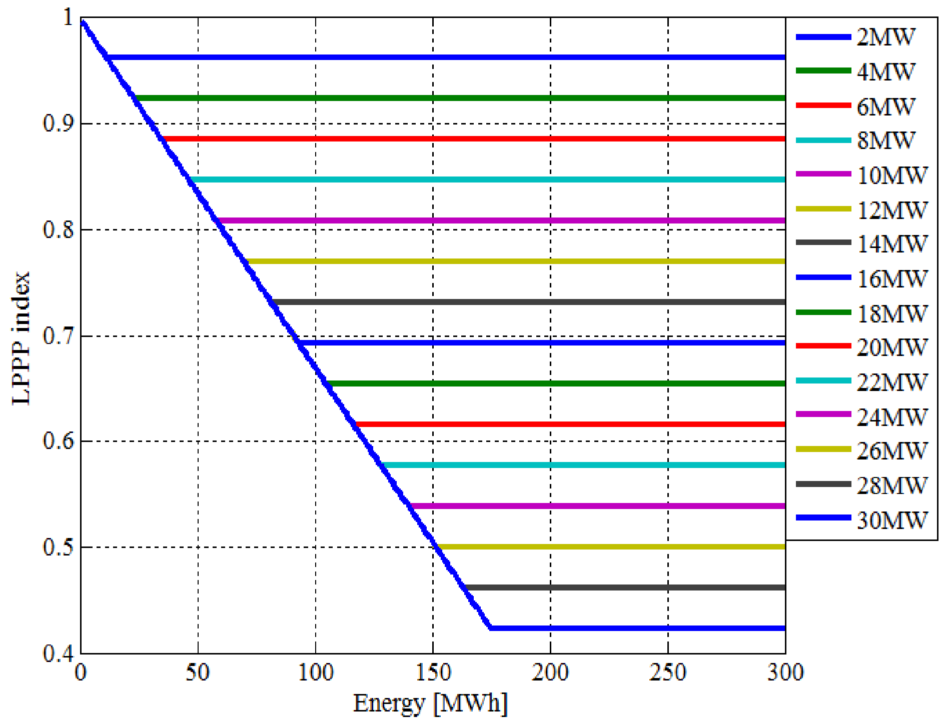


Figure 7.3- LPPP Vs. storage system rated energy.

Figure 7.3 shows the results of the LPPP analysis. Each curve of the figure shows a knee beyond which a further increase in the energy capacity would not lead to additional benefits. Beyond that value, in fact, depending on power rating, additional amounts of energy can not be stored.

Each knee is a potential design of the energy storage system in terms of rated power (MW) and capacity (MWh) since in this case the full retrieve of the produced energy is not required (LPPP=0). The following table summarizes the 15 solutions of the storage system (MW and MWh), the amount of energy released during the day and the initial cost of the system.

Information about the cost of VRB for this application are provided by Prudent Energy in the view of a economic cooperation between the firms. For each potential solution an economic analysis is then performed considering the pay-back time (TPB) and the discounted cash flow (Net Cash Flow actualized cumulative) for the years exceeding the full return of the initial capital. The pay-back time refers to the period of time required for the return on an investment to "repay" the sum of the original investment. The discounted cash flow (DCF) analysis is a method of valuing a project, company, or asset using the concepts of the time value of money. All future cash flows are estimated and discounted, according to a risk-adjusted rate, to give their present values (PVs). In this analysis are considered only the sum of the present value for the years exceeding the pay-back period.

TABLE 7.I. Simulation results

Solution N°	Power [MW]	Energy [MWh]	Delivered Energy [MWh]	Initial Cost [€]
1	2	12	10.5	6780000
2	4	24	21	13560000
3	6	35	31.5	20075000
4	8	47	42	26855000
5	10	59	52.5	33635000
6	12	70	63	40150000
7	14	82	73.5	46930000
8	16	94	84	53710000
9	18	105	94.5	60225000
10	20	117	105	67005000
11	22	129	115.5	73785000
12	24	140	126	80300000
13	26	152	136.5	87080000
14	28	164	147	93860000
15	30	175	157.5	100375000

For this analysis, the energy price was fixed at 90 € / MWh, and the VRB costs to 1800 € / kW and 265 € / kWh, with an estimated annual maintenance of 1% per year. The amount of savings due to the fuel saved is evaluated on 60 € / MWh. Economic evaluations related to costs, revenues and earnings consider two different scenarios for the sale price of energy produced at night, namely: 0 € / MWh and 20 € / MWh. An inflation rate of 3.5% per year has been also considered. A 4.5% discount rate is considered to evaluate the discounted cash flows. It was also considered a 1% loss of the system annual efficiency and two extraordinary maintenance after 9 and 14 years respectively equal to 5% and 2.5% of initial cost. All the tax contributions considered is about 36%.

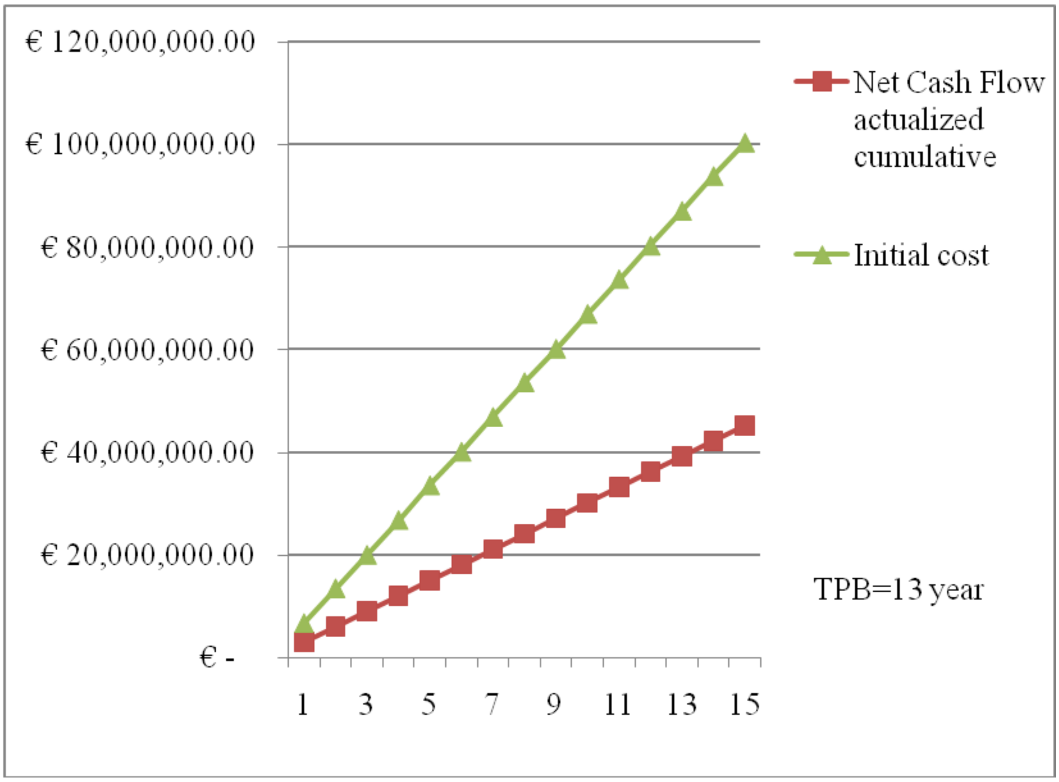


Figure 7.4 - Gains and initial costs with nightly 20€/MWh

Energy price 90€/MWh Saving 60€/MWh			
N	Net Cash Flow actualized cumulative	Initial cost	TPB
1	€ 3,010,630.02	€ 6,780,000.00	13
2	€ 6,021,260.04	€ 13,560,000.00	13
3	€ 9,040,121.59	€ 20,075,000.00	13
4	€ 12,050,751.61	€ 26,855,000.00	13
5	€ 15,061,381.63	€ 33,635,000.00	13
6	€ 18,080,243.17	€ 40,150,000.00	13
7	€ 21,090,873.20	€ 46,930,000.00	13
8	€ 24,101,503.22	€ 53,710,000.00	13
9	€ 27,120,364.76	€ 60,225,000.00	13
10	€ 30,130,994.78	€ 67,005,000.00	13
11	€ 33,141,624.80	€ 73,785,000.00	13
12	€ 36,160,486.35	€ 80,300,000.00	13
13	€ 39,171,116.37	€ 87,080,000.00	13
14	€ 42,181,746.39	€ 93,860,000.00	13
15	€ 45,200,607.94	€ 100,375,000.00	13

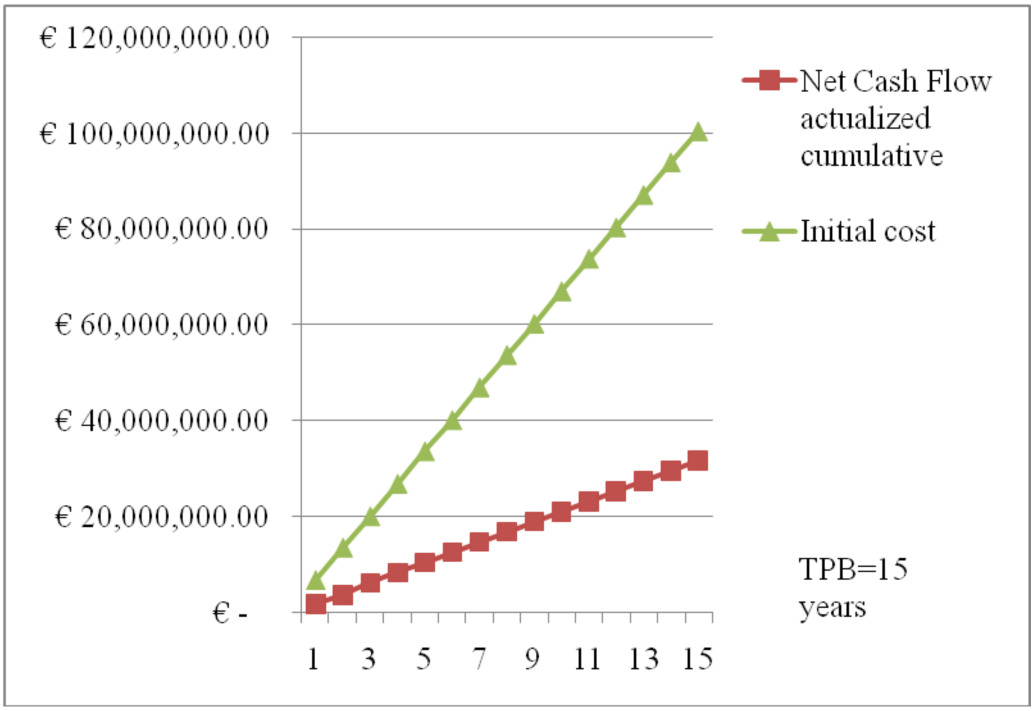


Figure 7.5 - Gains and initial costs with nightly 0€/MWh

Energy price 90€/MWh Saving 40€/MWh			
N	Net Cash Flow actualized cumulative	Initial cost	TPB
1	€ 1,797,385.01	€ 6,780,000.00	15
2	€ 3,594,770.01	€ 13,560,000.00	15
3	€ 5,942,826.47	€ 20,075,000.00	15
4	€ 7,919,366.20	€ 26,855,000.00	15
5	€ 9,895,905.93	€ 33,635,000.00	15
6	€ 11,885,652.94	€ 40,150,000.00	15
7	€ 13,862,192.67	€ 46,930,000.00	15
8	€ 15,838,732.40	€ 53,710,000.00	15
9	€ 17,828,479.41	€ 60,225,000.00	15
10	€ 19,805,019.14	€ 67,005,000.00	15
11	€ 21,781,558.87	€ 73,785,000.00	15
12	€ 23,771,305.88	€ 80,300,000.00	15
13	€ 25,747,845.61	€ 87,080,000.00	15
14	€ 27,724,385.34	€ 93,860,000.00	15
15	€ 29,714,132.35	€ 100,375,000.00	15

7.5 Conclusions

The proposed approach is a new interesting alternative solution to the energy management problems that occur in a power plant. The results are still heavily influenced by the high price of the VRB energy storage system.

However, each solution shows economic profit, and thus can be considered a good investment. Moreover it must be considered that the lifetime of the VRB (here considered 25 year) can be much longer with a constant maintenance, thus increasing the potential profits.

In a near future, a decreasing price of VRB-ESS due to a larger distribution, may lead these systems to be competitive if compared to other systems like pumped hydro.

Conclusions

The main objective of my research activity has been the development of advanced design techniques for energy storage devices tasked to equip generation systems from renewable energy sources. Several deterministic approaches have been commonly exploited in the past, to accomplish such a task, leading to suboptimal solutions. Therefore, probabilistic approaches have been considered to be applied on renewable energy plants either grid connected, either operating in island mode. Specifically, a reliability index, the L.P.S.P (*Loss Power Supply Probability*), has been considered. However, the basic L.P.S.P. approach has been modified to account for the features of advanced energy storage systems. Moreover, a new formulation of the L.P.S.P index has been carried out, to deal with grid connected systems.

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