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DEVELOPMENT OF A MICROGRID WITH RENEWABLE ENERGY SOURCES AND ELECTROCHEMICAL STORAGE SYSTEM INTEGRATION

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Abstract

Beside the traditional paradigm of "centralized" power generation with a few main power plants and a distribution network directly connected to the end-users, a new concept of "distributed" generation is emerging, in which the same user becomes pro-sumer, i.e. self-energy producer. During this transition, the Energy Storage Systems (ESS) can provide multiple services and features, which are necessary for a higher quality of the electrical system (both on transmission and on distribution) and for the optimization of non-programmable Renewable Energy Source (RES) power plants.

A ESS prototype was designed, developed and integrated into a renewable energy production system in order to create a smart microgrid and consequently manage in an efficient and intelligent way the energy flow as a function of the power demand. The produced energy can be introduced into the grid, supplied to the load directly or stored in batteries.

The microgrid is composed by a 7 kW wind turbine (WT) and a 17 kW photovoltaic (PV) plant are part of. The load is given by electrical utilities of a cheese factory.

The ESS is composed by the following two subsystems, a Battery Energy Storage System (BESS) and a Power Control System (PCS). With the aim of sizing the ESS, a Remote Grid Analyzer (RGA) was designed, realized and connected to the wind turbine, photovoltaic plant and the switchboard.

Afterwards, different electrochemical storage technologies were studied, and taking into account the load requirements present in the cheese factory, the most suitable solution was identified in the high temperatures salt $Na\text{-}NiCl_2$ battery technology. The data acquisition from all electrical utilities provided a detailed load analysis, indicating the optimal storage size equal to a 30 kW battery system. Moreover a container was designed and realized to locate the BESS and PCS, meeting all the requirements and safety conditions.

Furthermore, a smart control system was implemented in order to handle the different applications of the ESS, such as peak shaving or load leveling.

Acknowledgements

I would like to express my special appreciation and thanks to my advisors Professor Dr. Michele Bianchi and Professor Dr. Antonio Peretto, you have been a tremendous mentors for me. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. Your guidance helped me in all the time of research and writing of this thesis

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List of Acronyms

Acronym	Description
TS	Tozzi Storage
ESS	Energy Storage System
RES	Renewable Energy Source
PCS	Power Control System
BESS	Battery Energy Storage System
BMS	Battery Management System
TRE	Tozzi Renewable Energy
DC	Direct Current
AC	Alternating Current
LV	Low Voltage
ATU	Air Treatment Unit
WT	Wind Turbine
PV	Photovoltaic
REI	fire-resistance rating
TSO	Transmission System Operator
DSO	Distribution System Operator
HMI	Human Machine Interface
TMPC	Tozzi Master Power Control
TGA	Tozzi Grid Analyser
DOD	Depth of Discharge
SOC	State of Charge

GW	GateWay
UPS	Uninterruptable Power System
P	Active Power
Q	Reactive Power
LVFRT	Low Voltage Fault Ride Trough
HVFRT	High Voltage Fault Ride Trough
BDEW	Bundesverband der Energie- und Wasserwirtschaft
THD	Total Harmonic Distortion
BIST	Built In Self-Test
GHG	Greenhouse Gas
EU	European Union
EV	Electric Vehicle
V2G	Vehicle To Grid
AMI	Advanced Metering Infrastructure
DR	Demand Response
HAN	Home Automation Networks
DA	Distribution Automation
CSP	Control Solar Power
FIT	Feed-in Tariff
SUES	Stationery Utility Energy Storage
EAC	Energy Advisory Council
DG	Distributed Generation

1. Introduction

1.1 Background

The last couple of decades have been a great time of change for the power industry. There are many new and exciting areas in the field of electric power generation, distribution and storage that may be a potential solution to get a sustainable improvement of the grid one day. When looking for a solution to power the grid, the concept of sustainability implies that not only the factor of economics has to be considered but also feasibility and environmental issues as well.

Renewable or green solutions to power the grid are becoming ever more present as pressure on environmental issues is being put on industry from governments. One promising form of green energy is the use of large grid scaled energy storage. Energy storage is promising due to the multitude of applications that it can be used for.

Renewable generation sources such as wind power and solar power are generated by stochastic environmental processes such as the sun shining or the wind blowing and must be used instantaneously. Power that is generated by these energy sources can be used in the most effective manner by integrating energy storage solutions due to the fact that power generated by these stochastic processes sometimes cannot be used immediately and it is best stored until it is needed.

Energy storage can also be used for several maintenance purposes. Today's infrastructure is clearly aging and in need of modernization. One of the biggest problems that avoids the process of repairing and updating the grid is the grid's need to be energized at all times, especially when dealing with sensitive loads. Local energy storage systems can be used for local grid maintenance, rather than expensive and time consuming methods requiring a certain part of the grid to be de-energized.

1.2 Scope

In the last years, the grid is starting to experience problems of congestion, that is, the existing transmission and/or distribution lines are unable to accommodate all required load during periods of high demand or during emergency load conditions, such as when an adjacent line is taken out of service or damaged by a storm. Another cause is the quick growth of non-programmable renewable energy power plant, which can be produce instability in the grid, because of its intermittent generation of electrical energy and mismatches between generation and consumption profiles.

Based on this new grid situation, ESS are considered one of the most promising technologies to reduce the congestion problems of the grid and in turn, to optimize the RESs penetration.

The goal of this research project is the creation of a microgrid through the integration of an ESS into a farm, where two RES are installed (PV and WT plant). The installed system must be able to manage the flow energy from the RES and to the loads present in the farm, in order to reduce or eliminate the electricity consumption from the grid. Also, the system has to be flexible, that is, has the potential to be installed in different places with different configurations.

Firstly, a feasibility study, a design and development of an ESS prototype equipped with $Na\text{-}NiCl_2$ batteries will carried out in order to perform field tests. The ESS performance will have to be guaranteed in on-grid and off-grid mode.

The last goal will be the study and test of several applications such as peak shaving and load leveling.

1.3 Thesis Outline

Chapter 2 aims at providing a general introduction to the context of the deployment of renewable electricity in Italy in terms of electricity production, consumption, and grid operation

Chapter 3 and 4 present a new concept in the energy field: distributed generation and smart grid. These concepts are analysed, in particular the different type of distributed energy resources and the new challenges for the future. Also the main characteristic and features of a microgrid are described in chapter 4.

Chapter 5 presents an overview of the concept of Energy Storage and the need of integration into the future grid. A detailed analysis of the main electrochemical storage technologies is carried out.

Chapter 6, describes the project, the entire system and its components.

the project is described as well as the components of the system.

Chapter 7 offers a detailed analysis of the plant, focused on the analysis of the PV plant, WT plant and the loads of the farm.

Chapter 8 describes the system architecture, specifically hardware, software, mechanical and electrical architecture.

Chapter 9, describes all the civil works carried out in the farm to place the ESS and to connect it to the grid and to the other system components.

In Chapters 10 and 11, the system logic is studied. First the BESS is sized and the duty cycle is defined. Next step is the design and development of the PCS. Finally the control and supervision system, named Tozzi Master Power Control (TMPC) is described.

Chapter 12 describes how to communicate with the ESS from a remote point through the use of a modem/router HSPA which is installed within the switchboard. Also it is accessible from a local point through an Access Point.

Chapter 13 presents the first experiments carried out in the system in order to test both the ESS and the microgrid.

Last Chapter summarizes the work realized in the project and provides a critical analysis of the results obtained. Finally, a brief description of future changes and tests is given.

2. Renewable Electricity Deployment in Italy

2.1 Current Generation Mix and Net Generating Capacity

Italy is a large consumer and a net importer of electricity, making it a very relevant subject in the European context. Given its geographical features, Italy shows a large share of hydro generation. A graphical overview of Italy's electricity generation mix in 2010 is shown in Figure 1.

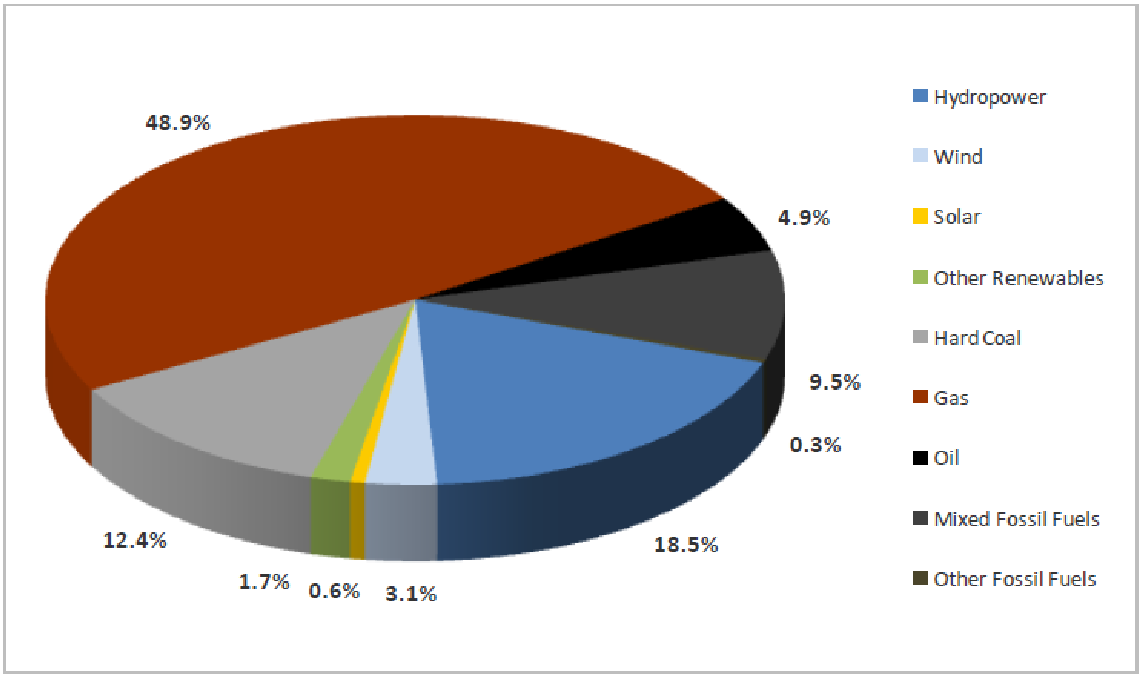

Figure 1 Generation Mix - 2010 (%) [1].

Power generation in Italy holds natural gas as its main production source, counting for about 46% of overall generation. Hydro power is by far the RES source with the largest share in overall production (18.5%). Given Italy's large amount of water resources, especially in the Alps, hydro power has been developed and largely exploited already in the past decades. As regards wind and solar, despite having had a steep increase in their shares in the last few years, they still amount only to 3.1% and 0.6% each in the overall generation share.

At a country level, thus, non-programmable RES still amount for a relatively minor share. Considering their characteristics together with the ones of hydro and gas, it appears that Italy should not suffer of any issue relating to the balancing of non-programmable capacity in the overall grid, as hydro and gas are programmable or relatively programmable sources that can quickly balance the network in case of need. This, however, should also be considered in the light of the status of the grid, now and in perspective. It is true that Italy can quickly fix unbalances, as it possesses a large share of controllable flexible sources. Non-programmable sources are concentrated in southern regions, though, and the transmission capacity of the grid in the centre-south may not always be sufficient to effectively balance RES generation variability. For these reasons, curtailment of RES plants, wind in particular, takes place in the centre-south of Italy. In 2010 wind energy was curtailed of about 470 GWh, equal to 5.6% of production [2].

The net generating capacity is provided in Figure 2.

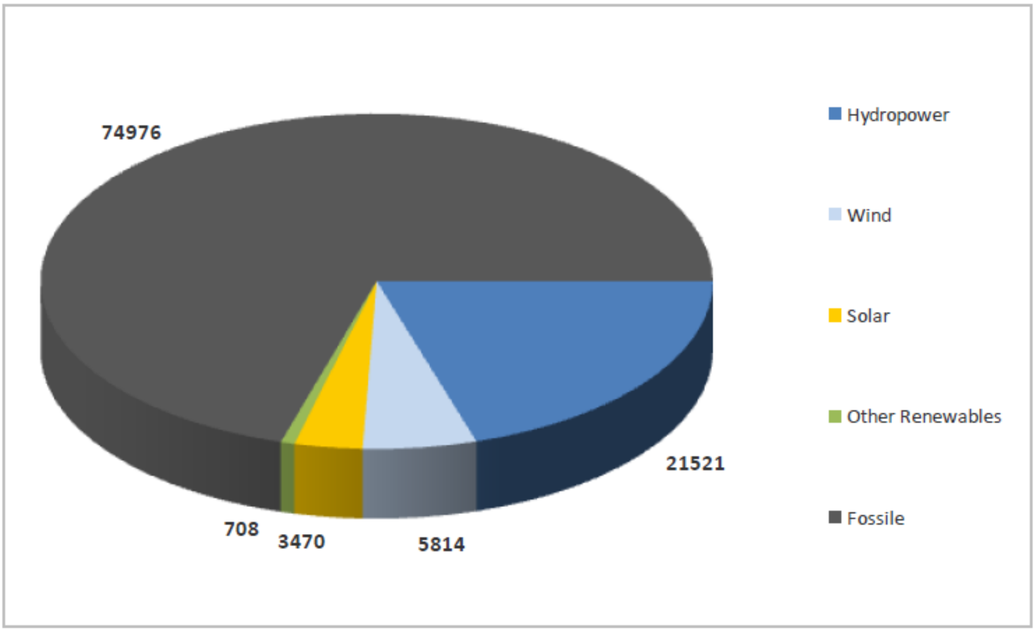

Figure 2 Net generating capacity - 2010 (MW) [1].

2.2 Electricity Consumption

In 2010, Italy consumed 330,455 GWh, i.e. circa 5.5 MWh per inhabitant, below the EU average of 6.2 MWh. In terms of electricity intensity of the economy, Italy has the 5th lowest value in Europe, consuming 213.2 MWh/M€ GDP, slightly below UK (220.2) and Germany (222.3) and below the EU average of 257.7 [1].

Considering the development of electricity consumption in time Italy's consumption's growth rate is quite average with respect to the EU 27, at around 2.1% per year on average between 1990 and 2007, a pace similar to the ones of Finland, the Netherlands and Belgium [3].

2.3 RES Share

Figure 3 provides an indication of Italy's total electricity consumption and RES electricity production up to 2020, according to the submitted action plan [4]. In other words, this is not a forecast, but the plan according to the government.

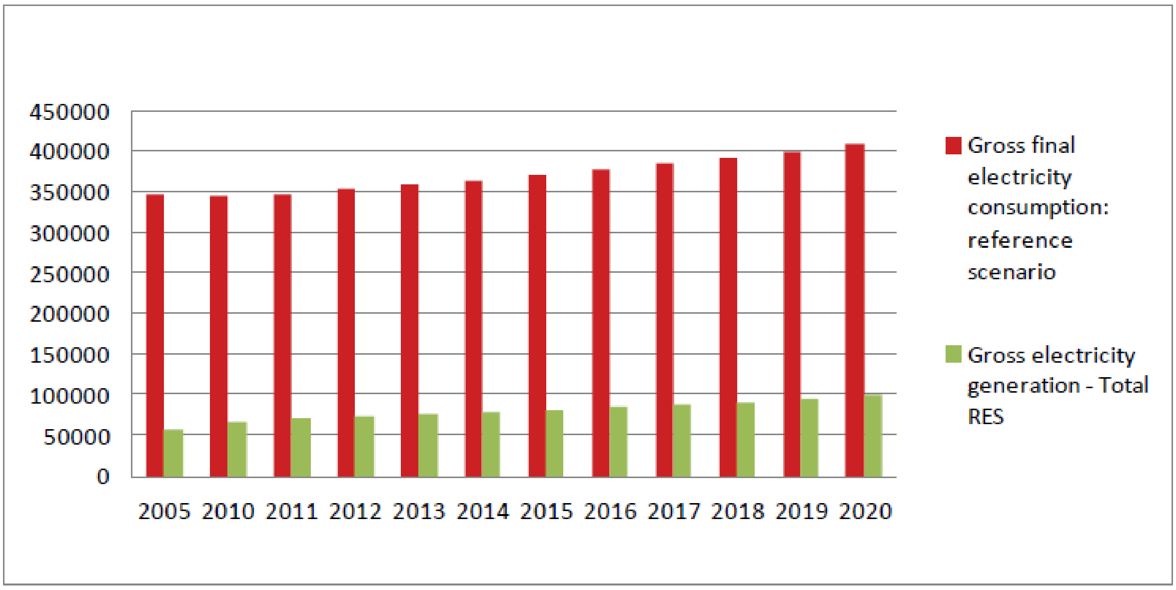

Figure 3 Electricity consumption and RES generation (GWh) [4].

According to the Italian NREAP, gross final electricity consumption is forecasted to grow from 343,143 GWh to 407,445 GWh (18% growth) between 2010 and 2020. RES production, in the same period, should grow from 66,791 GWh to 98,885 GWh (48% growth).

Comparing the above figures, the share of RES generation over gross final electricity consumption should grow from 19.46% in 2010 to 24.27% in 2020, this means that Italy, according to its plan, will be able to satisfy 19.46% and 24.27% of its internal electricity consumption through its internal production of RES in 2010 and 2020. This would nevertheless result in an increase of consumption from non-renewable generation and/or imports from 276,352 GWh/year in 2010 to 308,560 GWh/year in 2020. In comparison, historical data indicate that the share of RES generation over consumption went from 13.9% in 1990 to 15.6% in 1998, to 13.7% in 2003, to 16.6% in 2008 [5].

The evolution of renewable electricity generation is further broken down in Figure 4, which outlines the generation shares of wind, solar, hydropower and other RES to 2020. This graph is particularly interesting for the aim of this study as non-programmable sources (wind and solar) will require a grid infrastructure capable of supporting a high input variability. The higher the share of such sources, then, the more relevant the issue of grid adaptation will be. Hydropower, on the other hand, is a fairly controllable RES, which is well suited to balance the fluctuations on the network caused by wind and solar, thus a large share of this source, the larger the extent to which fluctuations can be mitigated.

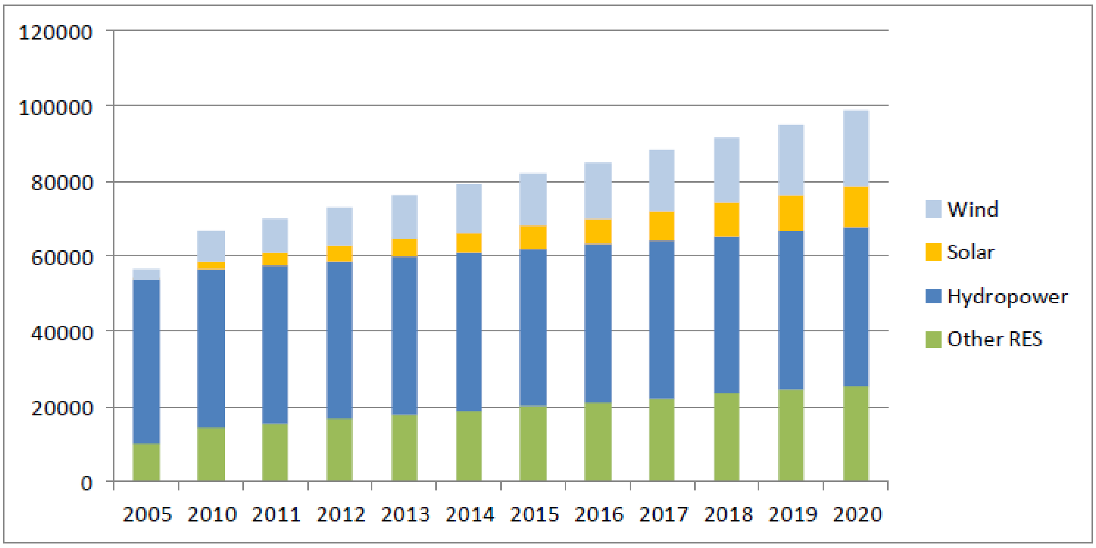

Figure 4 RES generation (GWh) [4].

Despite the large increase in non-programmable sources, the share of hydro power will still remain the largest one in Italy, thus smoothening concerns for balancing non-programmable capacity, though the location of hydro power plants, mainly in northern areas (whereas solar and wind are mostly located in the south), together with the relative scarcity of grid capacity may limit the efficacy of hydro in this sense.

2.4 Natural Resources and Geographical Structure

Following the context description, this section outlines some elements of the natural renewable resources of the country, and their geographical distribution. This is not meant as in-depth analysis, but rather as a rapid background for the analysis and recommendations in the following chapters.

- **Wind**

  As shown in Figure 5, the best wind resources in Italy are located in the south, particularly the Apennine Mountains and on the coast, as well as in the major islands. Also the relatively large off-shore potential is located in the southern coastal areas and islands. In perspective, this implies that a large share of non-programmable electricity would be fed into the grid in such areas. Unfortunately, the power grid in these areas is weak for historical reasons, since these areas are less densely populated and larger consumption centres are located in the North. Thus, the integration of further large resources requires a significant development of the grid, at local level and in terms of long distance transmission capacities.

- **Solar**

  The map shown in Figure 6 represents the yearly sum of irradiation in Italy. Due to high radiation, solar energy is considered a quite relevant technology for Italy.

  In terms of power storage capacities, Italy possesses a large amount of hydro systems in the North that were developed in the last decades and are fairly well integrated in the grid.

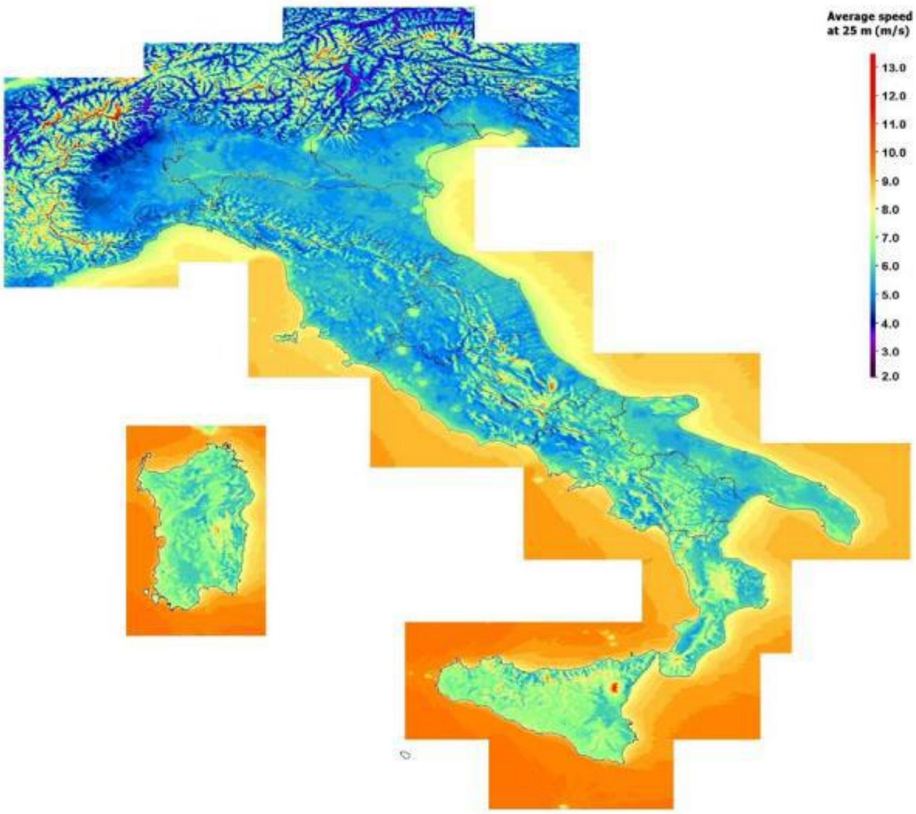

Figure 5 Map of wind resources at 25 meters above ground level [6].

Figure 6 Yearly sum of global irradiation on optimally inclined surface, 8 years average of the period 2001-2008 [kWh/m²] [7].

2.5 Grid Operators and Dominant Generators

As shown in Figure 7, power generation in Italy is split between several producers, the larger one being the ENEL group, which is also a former state monopoly, with a share in overall generation of 31.8% in 2009 and of 30% in 2010 [8]. It should be also underlined the fact that smaller producers amount for a total of about 17% in the country's generation.

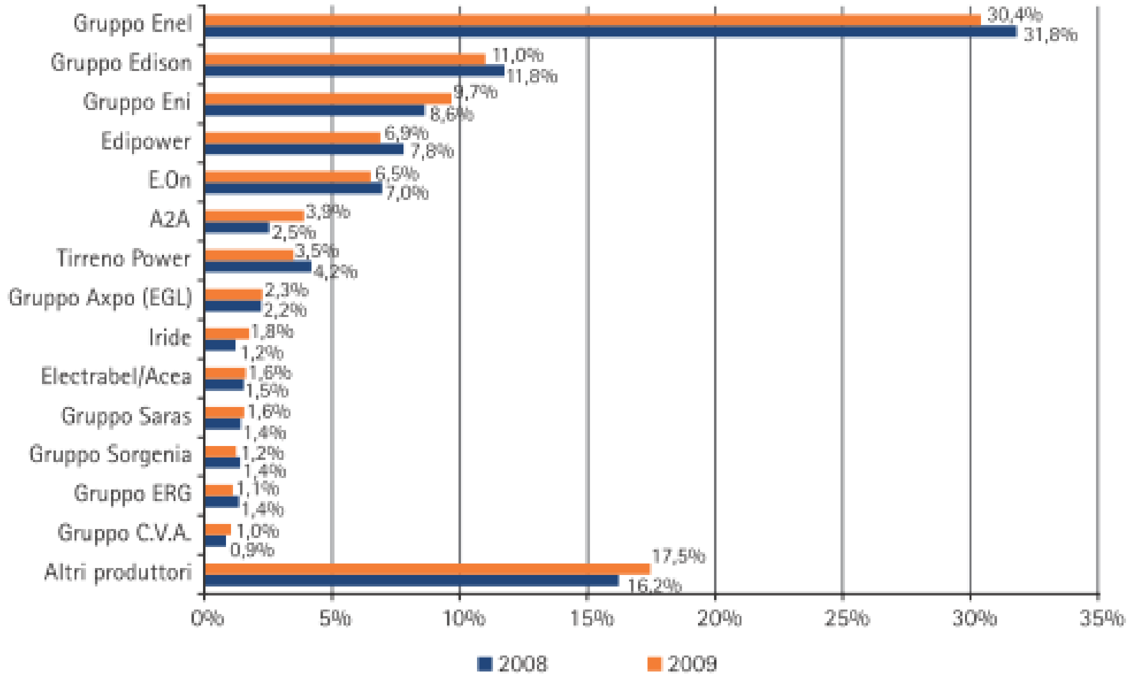

Figure 7 Share of overall generation in 2008 and 2009 [9].

Terna S.p.a. is the main transmission system operator in Italy, managing and owning about 62.000 km of high voltage lines and responsible for transmission and dispatching.

Transmission infrastructures were historically owned and operated by two different subjects: Terna had the ownership and GRTN operated them. The two companies have been merged in 2005. As of today Terna is the first independent operator in Europe and the seventh in the world for number of km.

In Italy there are about 150 DSOs, generally owned or grouped under larger companies. These larger companies are 29 in total and typically operate either on a city council level or on for larger areas.

Since April 1st, 2011, Terna publishes and updates an online register of DSOs.

2.6 Interconnections, Import/Export

Given its geographical position, and its ratio consumption / generation, Italy has interconnections with all neighbouring countries, as well as one with Greece. As shown in the table below, Italy is a net importer of electricity. In 2010, it imported 42.2 GWh net, i.e. circa 13.38% of its overall consumption.

GWh (2010)	AT	CH	FR	GR	SI	Total	% of consumption
Export	2	493	1012	72	120	1699	0.51%
Import	1328	23176	11583	2299	7513	45899	13.89%
Net	-1326	-22683	-10571	-2227	-7393	-44200	-13.38%
Total flows	1330	23669	12595	2371	7633	47598	14.40%

Table 1 Physical exchanges in Italian interconnected operation [1].

3. Distributed and Renewable Electricity Generation

3.1 Background

Whereas on a traditional grid, power generation was centralized and transmission and distribution were one-way, the metering capabilities and two-way communication of smart grids enable the production of electricity in numerous, decentralized locations. The growth of renewable power production, micro- or large scale, such as the offshore wind parks, is increasing the need for a smart grid that is able to balance these intermittent resources.

Distributed generation allows electricity to be produced by utilities or by individuals, closer to the point of consumption, thus reducing energy transmission loses. It helps utilities to meet peak power needs more easily and diversify the range of energy resources, lowering the cost of distribution and increasing the reliability of the power flow. Distributed generation also enables a more efficient use of waste heat from combined heat and power plants (CHP) and the possibility of smaller scale, modular expansion of capacity reduces capital [10].

Distributed generation is a driver behind the reduction of electricity costs for consumers, and increases the use of renewables. Power production in distributed locations can be small scale and individual 'prosumers' (consumers that also micro-produce) have the option to resell their production to the utility. This is completely changing the relationship between utilities and consumers.

The development of DG is driven by environmental concerns, deregulation of the electricity market, diversification of energy sources/energy autonomy and energy efficiency, while barriers are mainly technical constraints, such as design procedures, limitations on rural network capacity, fault level restrictions in urban areas and a lack of interconnection standards. Recently, increasing difficulties in obtaining planning permission, especially for wind turbines, has also become an obstacle in some countries. Various EU countries, such as Germany and Spain, have installed specific incentives and tax policies to promote DG development.

According to Capgemini [11], to meet 2020 EU targets, the volume of renewable energy generation connected to the grid is expected to triple from 150 GW to 450 GW. Small and medium size enterprises that specialize in ICT and electricity created by the integration of distributed electricity generation.

3.2 Economies of Scale

Historically, central plants have been an integral part of the electric grid, in which large generating facilities are specifically located either close to resources or otherwise located far from populated load centers. These, in turn, supply the traditional transmission and distribution grid which distributes bulk power to load centers, and from there to consumers. These were developed when the costs of transporting fuel and integrating generating technologies into populated areas far exceeded the cost of developing T&D facilities and tariffs. Central plants are usually designed to take advantage of available economies of scale in a site-specific manner, and are built as “one-off,” custom projects.

These economies of scale began to fail in the late 1960s and, by the start of the 21st century, Central Plants could arguably no longer deliver competitively cheap and reliable electricity to more remote customers through the grid, because the plants had come to cost less than the grid and had become so reliable that nearly all power failures originated in the grid. Thus, the grid had become the main driver of remote customers’ power costs and power quality problems, which became more acute as digital equipment required extremely reliable [12]. Efficiency gains no longer come from increasing generating capacity, but from smaller units located closer to sites of [13].

For example, coal power plants are built away from cities to prevent their heavy air pollution from affecting the populace. In addition, such plants are often built near collieries to minimize the cost of transporting coal. Hydroelectric plants are by their nature limited to operating at sites with sufficient water flow. Most fuelled power plants are too far away for their waste heat to be economically used for heating buildings.

Low pollution is a crucial advantage of combined cycle plants that burn natural gas. The low pollution permits the plants to be near enough to a city to be used for district heating and cooling.

Distributed generation plants are mass-produced, small, and less site-specific. Their development arose out of:

- concerns over perceived externalized costs of central plant generation, particularly environmental concerns,
- the increasing age, deterioration, and capacity constraints upon T&D for bulk power,
- the increasing relative economy of mass production of smaller appliances over heavy manufacturing of larger units and on-site construction, and
- along with higher relative prices for energy, higher overall complexity and total costs for regulatory oversight, tariff administration, and metering and billing.

Capital markets have come to realize that right-sized resources, for individual customers, distribution substations, or microgrids, are able to offer important but little-known economic advantages over Central Plants. Smaller units offered greater economies from mass-production than big ones could gain through unit size. These increased value due to improvements in financial risk, engineering flexibility, security, and environmental quality of these resources can often more than offset their apparent cost [14]. DG, vis-à-vis Central Plants, must be justified on a life-cycle basis. Unfortunately, many of the direct, and virtually all of the indirect, benefits of DG are not captured within traditional utility cash-flow accounting.

While the levelled generation cost of distributed generation is more expensive than conventional sources on a kWh basis, this does not include a complete accounting for the negative externalities associated with conventional fuels. The additional premium for DG is rapidly declining as demand increases and technology progresses, and sufficient and reliable demand will bring economies of scale, innovation, competition, and more flexible financing, that will make DG clean energy part of a more diversified future.

Distributed generation reduces the amount of energy lost in transmitting electricity because the electricity is generated very near from where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be constructed.

Typical distributed power sources in a Feed-in Tariff (FIT) scheme have low maintenance, low pollution and high efficiencies. In the past, these traits required dedicated operating engineers and large complex plants to reduce pollution. However, modern embedded systems can provide these traits with automated operation and renewables, such as sunlight, wind and geothermal. This reduces the size of power plant that can show a profit.

3.3 Types of Distributed Energy Resources

- **Wind Energy**

Wind energy plants around the world produced 273 TWh of electricity in 2009, from an estimated installed capacity of 159 GW. IEA's estimates of 2009 wind energy generation and capacity by region and country are provided in Figure 8 and Figure 9 [15]. Wind power developments in 2010 have been substantial: China installed over 16 GW of new wind capacity in 2010, bringing its total to 42 GW. This exceeded the US 2010 total of 40 GW, and made China the world leader in wind capacity for the first time. Europe installed nearly 10 GW of wind in 2010, bringing its total capacity to 86 GW, over half of which is located in Germany and Spain.

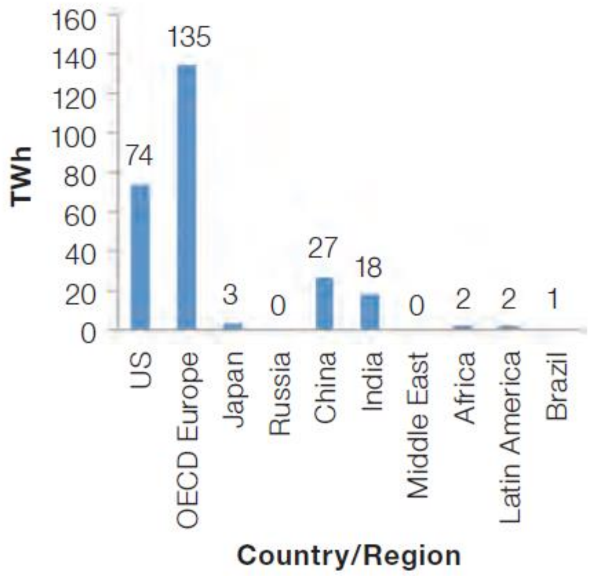

Figure 8 Wind energy generation by country/region in 2009

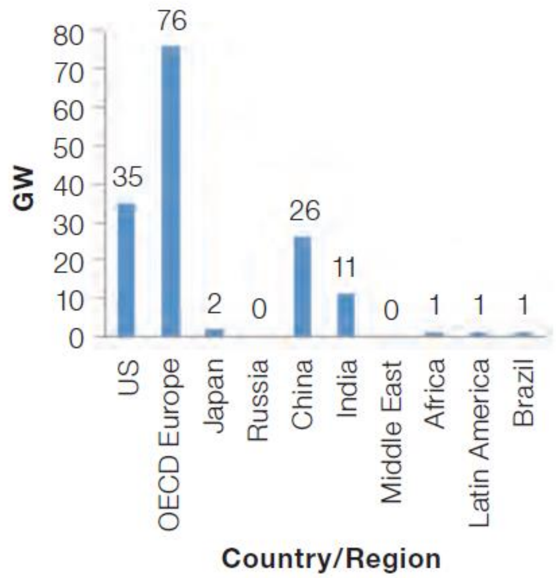

Figure 9 Wind energy capacity by country/region in 2009

IEA's New Policies Scenario projects 1282 TWh of annual wind-generated electricity globally by 2020 [15], a 369 % increase from 2009. By 2030 that figure reaches 2182 TWh, a near doubling of the 2020 estimate over the course of a decade, as shown in Figure 10. In terms of capacity, IEA projects growth from 159

GW in 2009 to 582 GW in 2020, reaching 1102 GW by 2035, as shown in Figure 11 [15].

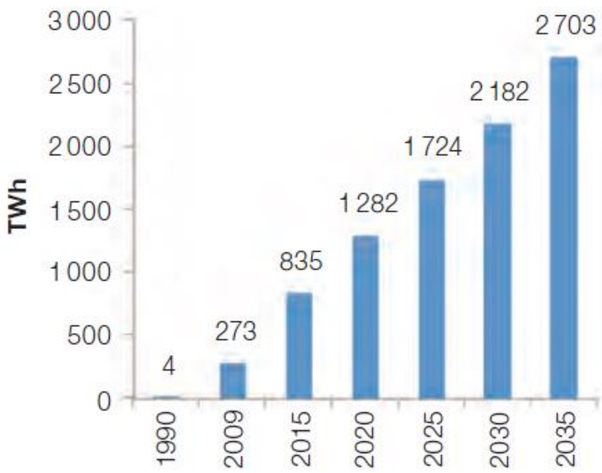

Figure 10 Global wind energy generation projections to 2035

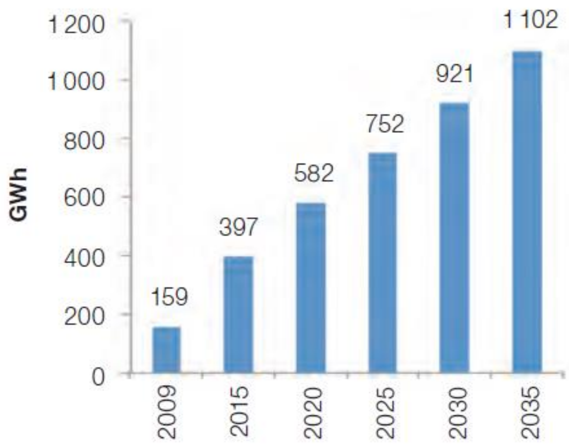

Figure 11 Global wind energy capacity projections to 2035

Wind capacity growth over this period is dominated overwhelmingly by China, OECD Europe and the USA, as shown in Figure 12. Indeed, while the current disparity between these countries and the rest of the world in wind capacity is stark, it is dwarfed by future growth estimates, by which the leaders will outpace the others by orders of magnitude. OECD Europe and China maintain growth in lockstep through 2035, leaving the USA somewhat behind, though still a major player. It is also apparent that Latin America's growth in renewables overall does not translate to a significant growth in wind.

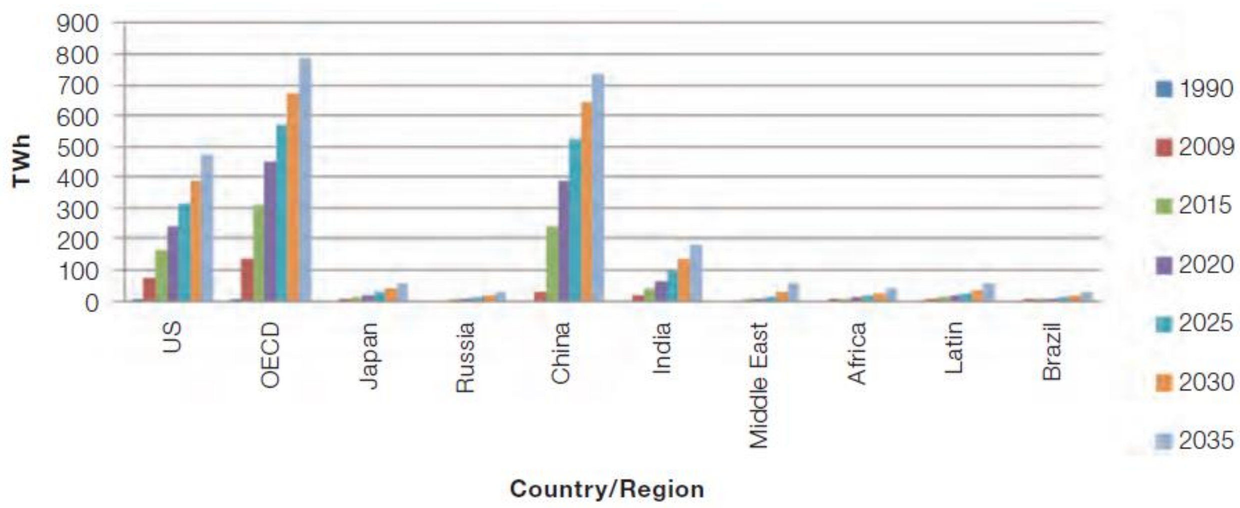

Figure 12 Wind energy generation to 2035 by region/country

Regionally, the OECD European countries together show the strongest wind growth, slightly outpacing China. 76 GW of European wind power produced 135 TWh of electricity in 2009 [15]. Germany, Spain, Italy and France are the major contributors to wind energy capacity in this region. In Europe, the majority of wind farms developed during the past ten years have been onshore and small-capacity. With many wind-rich areas now thoroughly exploited, European wind developers are turning their attention to large-capacity offshore wind farms with centralized integration to the power grid.

By 2020, IEA projects wind capacity of 209 GW and 449 TWh of generation in Europe. By 2030, capacity reaches 289 GW and generation reaches 675 TWh [15]. Germany has set a target of 45.75 GW of wind capacity for 2020 [16], and Spain a target of 38 GW [17]. These plans contribute substantially to Europe's regional estimate, particularly in the next decade.

If we examine single countries rather than regions, China is the world's tour de force in wind power development. 26 GW of wind power supplied 27 TWh of electricity in China in 2009, ranking it third globally in wind capacity. A year later, China had jumped into first place with a total of 42 GW in 2010 [18]. China is set to lead the world in wind generation and wind capacity by 2035. The IEA predicts China will produce 388 TWh of electricity from wind in 2020, and the National Energy Administration (NEA) of China has set a target of 150-180 GW of wind capacity by the same date [19], which matches IEA's estimate of China's installed wind capacity of 180 GW. By 2030, IEA projects that China will reach 280 GW of wind capacity, just behind estimates for the combined European countries.

US wind capacity stood at 35 GW in 2009, generating 74 TWh of electricity. Most of US wind capacity is concentrated in the states of Texas, Iowa, California, Michigan and Washington, and is onshore. As a result of declining energy demand, an economic recession and a precipitous drop in North American natural gas prices, the USA did not keep pace with Europe and China in 2010, installing only 5 GW to Europe's 10 GW and China's 16 GW. Still, the USA is expected to remain a significant player in wind. IEA projects that US wind generation will grow to 165 TWh by 2015, more than double its 2009 value. By 2030, the capacity grows to 388 TWh from 151 GW [15].

Japan's 2 GW of wind capacity produced 3 TWh of electricity in 2009. IEA estimates Japanese wind capacity to grow to 7 GW by 2020, producing 18 TWh of electricity, and to 15 GW by 2030, producing 41 TWh of electricity [weo11]. Though these numbers are dwarfed by those from geographically larger regions such as China, OECD Europe and the USA, it is worth noting that the expected rate of increase of wind generation and capacity on the Japanese grid is dramatic: generation is expected to grow by 650 % between 2009 and 2030 under the IEA's New Policies Scenario [15].

The figures above do not differentiate between onshore and offshore wind. However, the sorts of integration challenges presented may differ between onshore and offshore wind projects, specifically with regard to the need for special transmission technologies for offshore plants. We therefore briefly examine the offshore segment of the wind market, which at present exists almost entirely in Europe, with a few projects in China.

Europe's offshore wind capacity stood at 4 GW at the end of 2011, with an additional 6 GW under construction at the time and 17 GW consented to by EU member states [20]. The majority of these projects are in the UK, Denmark and Germany, with some projects in Belgium, the Netherlands and Sweden. The European Wind Energy Association (EWEA), an industry association, projects that Europe will have 40 GW of offshore wind by 2020 producing 148 TWh of energy, and 150 GW producing 562 TWh by 2030. While industry estimates must be taken with the proverbial grain of salt, these numbers at least plausibly harmonize with IEA's OECD European wind (off- and onshore) projections of 209 GW by 2020 and 298 GW by 2030. EWEA itself identifies the availability of high voltage direct current transmission (HVDC) as a critical bottleneck for the development of offshore wind in Europe.

- **Solar Energy**

Grid-relevant solar energy technologies can be divided into two types: PV and concentrated solar power (CSP). PV generates electricity directly, converting sunlight to electricity through a semiconductor such as silicon. CSP technologies produce electricity by reflecting and concentrating sunlight onto a fluid, which then heats and boils water, the steam from which then drives a turbine that produces electricity. Presently, CSP has a lower contribution to RE production than solar PV. We will discuss each market in turn, beginning with the larger PV market.

Solar PV generated 20 TWh of electricity from 22 GW of global capacity in 2009 (see Figure 13 and Figure 14) [15]. The OECD Europe region far surpassed all other regions in both capacity and generation, despite its relatively weak solar resource. This apparent discrepancy is explained by highly favourable policy environments for solar PV in many European countries.

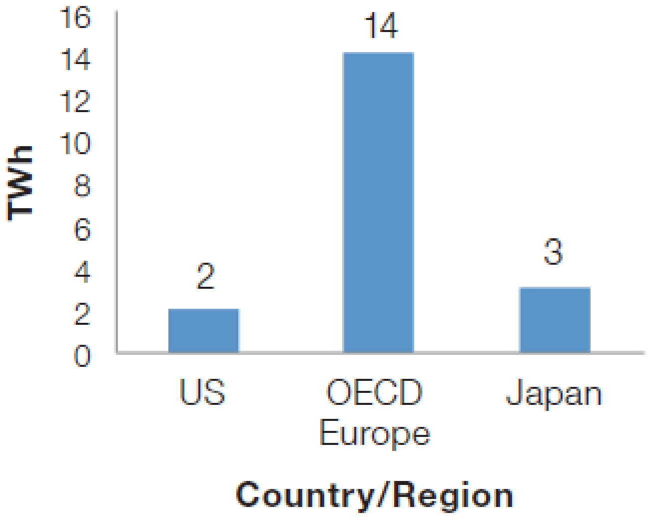

Figure 13 Solar PV energy generation in 2009 by country/region

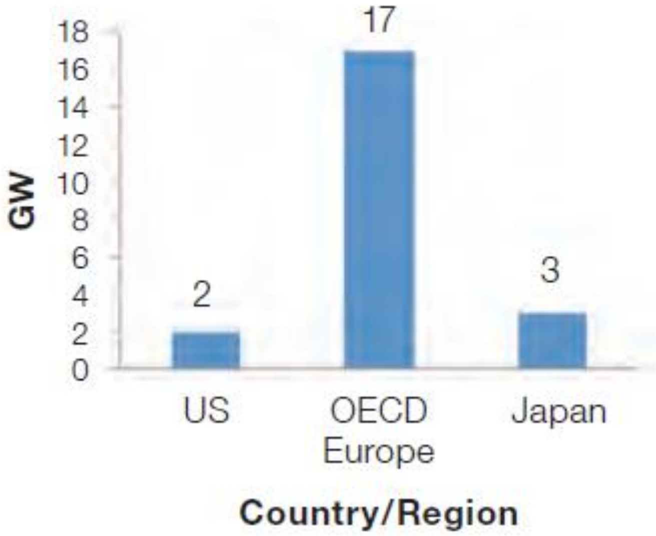

Figure 14 Solar PV energy capacity in 2009 by country/region

Though solar PV capacity is many times smaller than wind capacity at present, it is expected to grow at a faster pace than wind over the next several decades. The IEA projects solar PV generation of 230 TWh from 184 GW of capacity in 2020, an over 1000 % generation increase from 2009. By 2030, those figures reach 551 TWh and 385 GW, more than double the 2020 estimates. Figure 15 and Figure 16 display IEA's projections for solar PV energy production to 2035 [15].

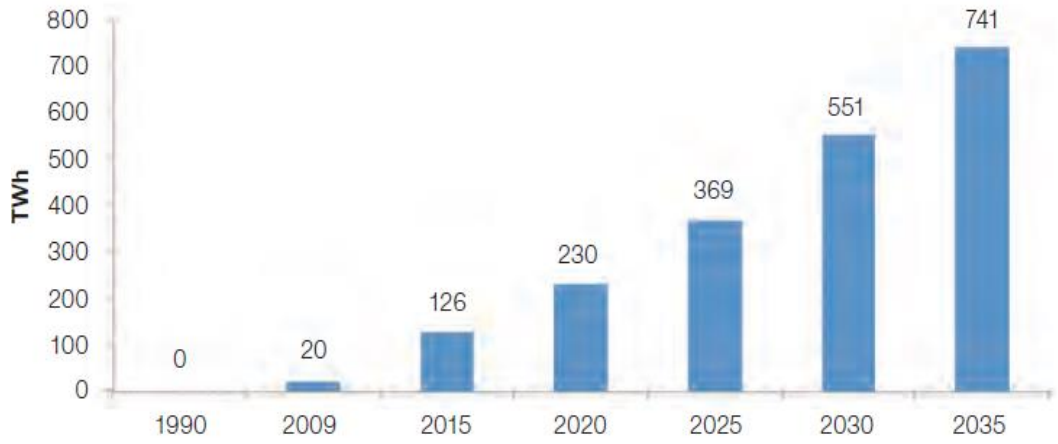

Figure 15 Energy generation from solar PV globally

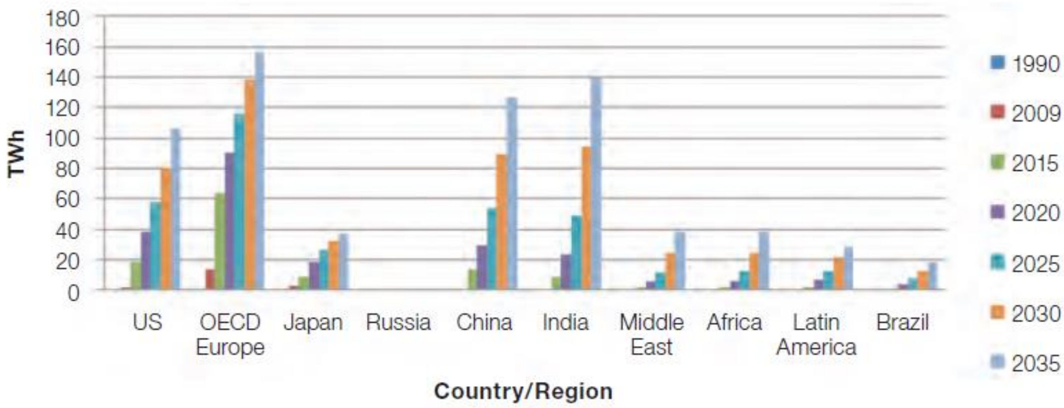

Figure 16 Energy generation from solar PV by country/region

In the OECD Europe region, solar PV produced 14 TWh of electricity from 17 GW of solar PV capacity in 2009. Favourable government policies and pricing have led to higher penetrations, particularly in Spain, Italy and Germany. In Germany, the government has opted for a feed-in tariff, in which the utilities pay the owner of a solar PV system a set tariff for renewable power over a period of time [21]. Consequently, solar PV provided 3 % of the total power in Germany in 2011 [22]. Germany led the world in PV capacity in 2009 with 9785 MW. Spain's 2009 capacity figure, at 3386 MW, was lower but still substantial in comparison to other countries [23]. Italy has ramped up solar PV capacity dramatically since then, reaching 12 750 MW and producing 10 TWh of energy in 2011 [24].

IEA projects 90 TWh from 84 GW of OECD European capacity by 2020 and 139 TWh from 115 GW by 2030. Germany expects its solar PV capacity to reach 52 GW by 2020 [16], and Spain estimates 8.4 GW by the same year [17]. It is worth noting that Europe's generation capacity factors (the ratio of energy generated from a given unit of power) for solar PV are lower than those for the USA. This disparity is explained by differences in the quality of the resource: the USA receives much more sunlight than Europe. Nevertheless, Europe's policy environment provides substantially more support to solar power, particularly in Germany and Spain, than does the US policy environment, explaining the capacity estimate differences as well as the ultimately higher generation estimates for Europe.

US solar PV generated 2 TWh of electricity from 2 GW of capacity in 2009. IEA estimates US solar PV generation at 38 TWh from 25 GW of capacity in 2020 and 81 TWh from 50 GW of capacity in 2030. Note that the 2030 estimate for US solar PV capacity is roughly a third of estimated US wind power capacity in the same year.

Japan generated 3 TWh of its electricity from solar PV sources in 2009 from 3 GW of capacity. By 2010, Japan had increased its solar PV capacity to 3.6 GW. This increase is attributable to a subsidy programme for residential PV system installations and another programme to purchase surplus PV power from small systems at double the retail electricity price. IEA projects 18 TWh of electricity from 17 GW of Japanese solar PV by 2020, and 32 TWh from 28 GW by 2030 [15].

China did not produce any significant amounts of electricity from solar PV in 2009, but that is changing rapidly, as it has become a manufacturing leader in the technology. IEA projects that China will produce 29 TWh from 20 GW of solar PV by 2020, and 89 TWh from 58 GW by 2030. This places China behind the USA in solar PV generation in 2020, but ahead of it by 2030. China's National Development and Reform Commission has set targets for China to achieve 10 GW of solar capacity in 2015, and 50 GW of solar capacity installed by 2020 [25].

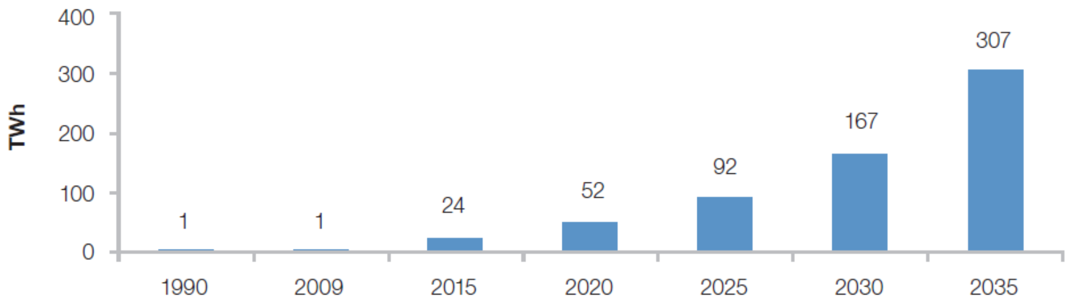

Figure 17 Global CSP energy generation to 2035

CSP's market is much smaller than wind power or solar PV, and it is less challenging to integrate into the power system due to its thermal aspects, which reduce variability in output. CSP produced 1 TWh of electricity in 2009 from a global capacity of 1 GW, located primarily in the USA, though Spain has since taken the lead [15].

CSP generation estimates are lower than those for PV, but exhibit similar strength in growth rates. IEA projects 52 TWh of CSP-generated energy from 14 GW of capacity in 2020, and 167 TWh from 45 GW in 2030. Figure 17 displays IEA's projections for global CSP generation to 2035 [15].

Spain led the world in 2010 in CSP capacity at over 632 MW. Spanish CSP capacity grew by 400 MW in 2010 due to a Royal Decree from the Spanish government that provided incentives for solar energy. In 2011, it began construction on nearly 1 GW of additional CSP capacity [17]. IEA projects 14 TWh of electricity from 4 GW of CSP sources in OECD Europe by 2020. In 2030, that rises to 36 TWh from 10 GW. The Spanish government, however, estimates that Spain alone will install 5 GW of CSP to produce 15.35 TWh by 2020, more than IEA's projection for all of Europe.

IEA projections for US CSP closely track those for OECD Europe, with 14 TWh from 4 GW in 2020, and 30 TWh from 8 GW in 2030.

3.4 Renewable Energy Integration Challenges

Wind and solar generation both experience intermittency, a combination of non-controllable variability and partial unpredictability, and depend on resources that are location dependent [26]. These three distinct aspects, explained below, each create distinct challenges for generation owners and grid operators in integrating wind and solar generation.

- **Non-controllable variability**: wind and solar output varies in a way that generation operators cannot control, because wind speeds and available sunlight may vary from moment to moment, affecting moment-to-moment power output. This fluctuation in power output results in the need for additional energy to balance supply and demand on the grid on an instantaneous basis, as well as ancillary services such as frequency regulation and voltage support. Figure 18 provides a graphical example of hourly wind power variability.

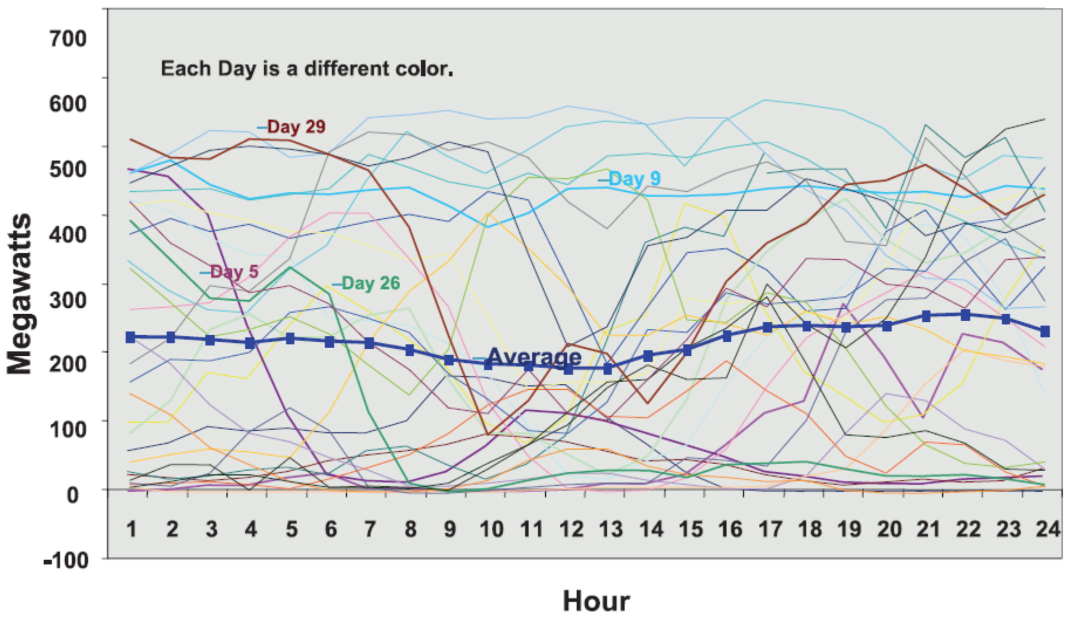

Figure 18 Hourly wind power output on 29 different days in April 2005 at the Tehachapi wind plant in California [27].

- **Partial unpredictability:** the availability of wind and sunlight is partially unpredictable. A wind turbine may only produce electricity when the wind is blowing, and solar PV systems require the presence of sunlight in order to operate. Figure 19 shows how actual wind power can differ from forecasts, even when multiple forecast scenarios are considered. Unpredictability can be managed through improved weather and generation forecasting technologies, the maintenance of reserves that stand ready to provide additional power when RE generation produces less energy than predicted, and the availability of dispatchable load to “soak up” excess power when RE generation produces more energy than predicted.

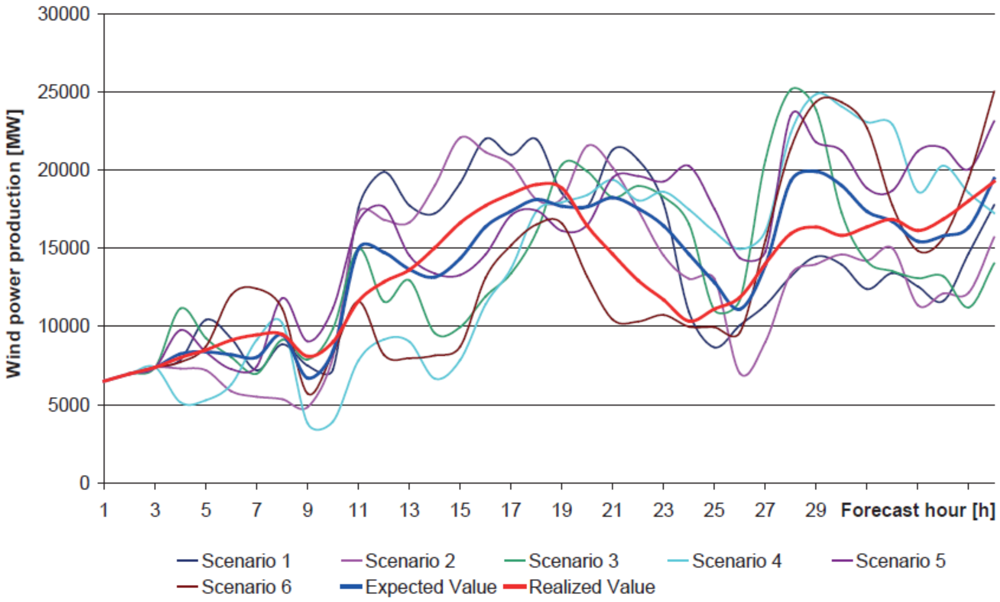

Figure 19 Example of a day-ahead forecast scenario tree for the wind power forecast for the PJM region of the United States [28].

- **Location dependence:** The best wind and solar resources are based in specific locations and, unlike coal, gas, oil or uranium, cannot be transported to a generation site that is grid-optimal. Generation must be collocated with the resource itself, and often these locations are far from the places where the power will ultimately be used. New transmission capacity is often required to connect wind and solar resources to the rest of the grid. Transmission costs are especially important for offshore wind resources, and such lines often necessitate the use of special technologies not found in land-based transmission lines. The global map in Figure 20displays the latest data on mean land-based wind speeds around the world.

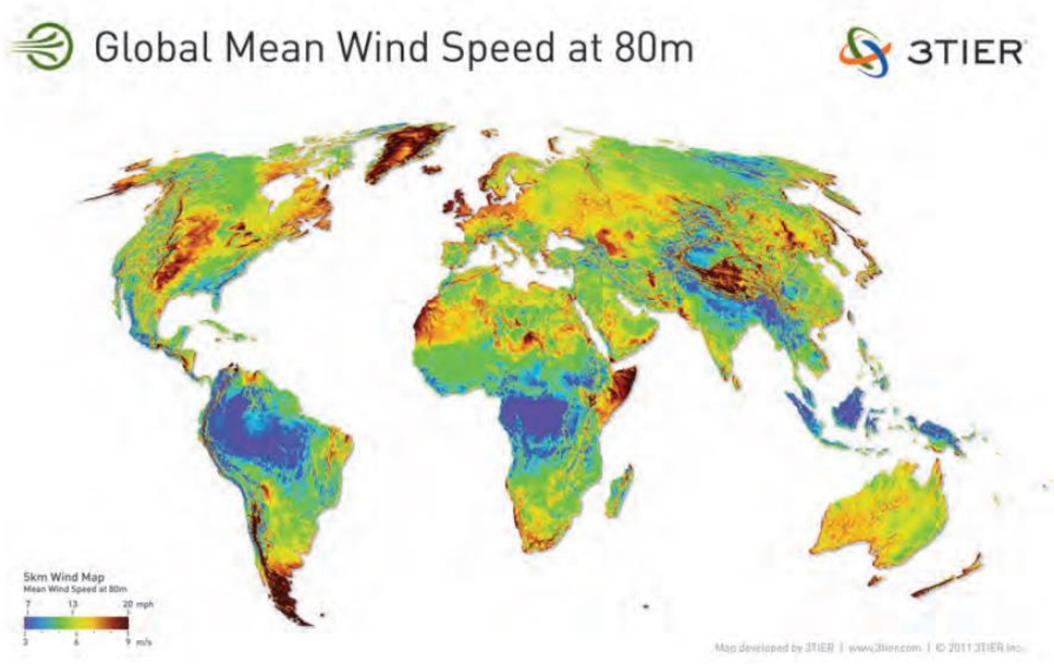

Figure 20 Global mean wind speed at 80 m altitude [29].

Because the presence of wind and sunlight are both temporally and spatially outside human control, integrating wind and solar generation resources into the electricity grid involves managing other controllable operations that may affect many other parts of the grid, including conventional generation. These operations and activities occur along a multitude of time scales, from seconds to years, and include new dispatch strategies for rampable generation resources, load management, provision of ancillary services for frequency and voltage control, expansion of transmission capacity, utilization of energy storage technologies, and linking of grid operator dispatch planning with weather and resource forecasting.

The essential insight to integration of variable RE is that its variability imposes the need for greater flexibility on the rest of the grid, from other (controllable) generators to transmission capacity to loads. Discussion of variable generation operation alone is insufficient to describe the full impact of high penetrations of RE on power system operation. Thus this report explores RE integration from both a plant operator and a system operator perspective, so as to identify the full range of operations involved [18].

- **Non-Controllable Variability**

  Variability in the context of wind and solar resources refers to the fact that their output is not constant. It is distinct from unpredictability, which we discuss in the following section. Even if operators could predict the output of wind and solar plants perfectly, that output would still be variable, and pose specific challenges to the grid operator, which we introduce here [18].

  On the seconds to minutes time scale, grid operators must deal with fluctuations in frequency and voltage on the transmission system that, if left unchecked, would damage the system as well as equipment on it. To do so, operators may order generators to inject power (active or reactive) into the grid not for sale to consumers, but in order to balance the actual and forecasted generation of power, which is necessary to maintain frequency and voltage on the grid. These ancillary services go by a plethora of names and specific descriptions. Typical services for an impressionistic overview include:

- **frequency regulation:** occurs on a seconds-to-minutes basis, and is done through automatic generation control (AGC) signals to generators;
- **spinning reserves:** generators available to provide power typically within 10 minutes. These reserves are used when another generator on the system goes down or deactivates unexpectedly;
- **non-spinning reserves:** these generators serve the same function as spinning reserves, but have a slower response time;
- **voltage support:** generators used for reactive power to raise voltage when necessary;
- **black-start capacity:** generators available to re-start the power system in case of a cascading black-out.

Additionally, grid operators must track loads demand for electricity on the consumption side of the grid and ensure that generation matches load at all times. This load following function becomes particularly important at times of day when demand for electricity increases substantially, such as morning, a hot afternoon, or evening. Load following may be provided through a class of ancillary service or through a "fast energy market", depending on the system operator.

These functions are not new. Grid operators have been regulating frequency and voltage, maintaining reserves and following shifts in load since the development of the electricity grid. This is because loads themselves are variable, and even conventional, controllable generation experiences problems and cannot perform as scheduled all of the time. Consumers demand electricity in ways that, while predictable, are not controllable and have some degree of variability. Thus wind and solar generation does not introduce entirely novel problems with which operators have never grappled. Indeed, at low penetrations, the integration challenges are primarily device and local-grid specific, such as subsynchronous resonance and harmonics, which the turbine itself may cause.

However, high penetrations of wind and solar generation will add more variability to the energy system than grid operators have traditionally managed in the past, and thus increase demand for ancillary services and balancing energy overall. It is more difficult, and sometimes impossible, to manage such challenges at the device level, and so grid-level actions, technologies and strategies are often needed. Wind and solar resources in sufficient amounts may also complicate load following functions when large demand shifts coincide with weather events that alter power output from wind or solar resources. Grid operators located in more remote regions and serving smaller loads may have less flexibility to provide ancillary services and load following than their larger counterparts. Compounding matters, plentiful RE resources are often located in these remote locations. The IEA and other bodies have recommended consolidation of grid operators, in order to integrate RE sources over larger areas and so reduce the variance of the power produced, as well as easing of market restrictions on sales of ancillary services as a solution to this problem [30].

4. Smart Grid

4.1 Introduction

Electricity has been a powerful driver of economic growth and wellbeing worldwide. Electricity generation is forecast to grow from 18,800 TWh in 2007 to 35,200 TWh in 2035 [31].

However, electricity consumption alone is causing 17% of anthropogenic greenhouse gas (GHG) emissions [32] and as such should be one of the main areas of focus for mitigation of climate change.

In the EU-27, gross electricity generation is expected to grow from 3,362 TWh in 2007 to at least 4,073 TWh in 2030, not even taking into account the possibility of significantly higher demand because of deployment of electric vehicles (EV) [33]. Most of Europe's energy needs are supplied from fossil fuel resources, largely imported into the European Union.

Energy demand continues to increase, while fossil fuel resources are shrinking and set to steadily become more expensive. At the same time, climate change and pollution have become issues of concern to European citizens. Through EU Directive 2009/28/EC, the EU has set an ambitious 20-20-20 target for 2020, committing to increase renewables' share of energy production to 20%, increase energy efficiency by 20% and lower CO_2 emissions by 20% compared to 1990 levels.

The smart grid is hailed by regulators and industry players as one of the key opportunities to save energy and lower CO_2 emissions, but deployment of the smart grid seems slow [34], [35].

The smart grid is a complex concept, involving not only distribution of electricity, but also data generation and communication systems and complex management applications. It also involves a wide variety of players, from electricity producers, grid operators and electricity retailers to hardware and software producers, industry giants and start-ups, investors, regulators and ‘prosumers’ (consumer and micro producer).

Greentech and Electricity Utilities as leading growth areas over the coming ten years. It is the convergence of these three sectors that creates the smart grid, which makes this one of the most exciting sectors to emerge [36]. The upgrading of old electricity grids with information and communication technology to modern ‘smart’ grids facilitates the integration of renewable energy and improves operational efficiency of the grids. It also enables savings in end consumption of electricity and allows for shifting of demand load through the involvement of empowered consumers , thus reducing the need for construction of expensive extra peak capacity.

Energy efficiency measures generally have a lower GHG abatement cost than investment in nuclear or renewable power generation or carbon capture & storage. smart grid technology and applications have the potential to increase the efficiency of electricity distribution as well as the efficiency of in-home electricity use. This is an incentive for policy makers, utilities and scientists to prioritize the development of the smart grid [37] .

4.2 Smart Grid Concept

The term “Smart Grid” was coined by Andres E. Carvallo on April 24, 2007 at an IDC (International Data Corporation) energy conference in Chicago, where he presented the smart grid as the combination of energy, communications, software and hardware. His definition of a Smart Grid is that it is the integration of an electric grid, a communications network, software, and hardware to monitor, control and manage the creation, distribution, storage and consumption of energy. The 21st century smart grid reaches every electric element, it is self-healing, it is interactive, and it is distributed.

The term smart grid refers to a modernization of the electricity delivery system so it monitors, protects, and automatically optimizes the operation of its interconnected elements from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances, and other household devices [38].

The smart grid will be characterized by a two-way flow of electricity and information to create an automated, widely distributed energy delivery network. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near instantaneous balance of supply and demand at the device level [39].

A smart grid is the electricity delivery system (from point of generation to point of consumption) integrated with communications and information technology for enhanced grid operations, customer services, and environmental benefits [40].

The smart grid, therefore from the above definitions is summarized in the text box of Figure 21.

> **The Smart Grid**, in quintessence, is a blend of communications and electrical capabilities that consent to utilities to recognize, optimize, and standardize energy usage, costs of demand and supply, and the overall reliability & efficiency of the system. This enhanced technology allows electricity suppliers to interact with the power delivery system and reveal where electricity is being used and from where it can be drawn during times of crisis or peak demand.

Figure 21 Gist of the Smart Grid

In order to achieve a modern grid, a wide range of technologies have to be developed and implemented. These are the essential technologies that must be implemented by the grid operators and the managers to have tools and training that is needed to operate modern grid [37].

4.3 Today’s Grid and Smart Grid

The grid as it exists today was originally designed more than fifty years ago, long before the creation of computer and telecommunication systems that we rely on today. The pressure that our increased power-needs exercise on the grid is shown through interruption of service and occasional blackouts, which pose significant economic and safety threats to our society. Smart grids have the potential to offer a number of advances, including some that automatically monitor and evaluate grid conditions, and report these conditions back to the utility‘s control room when they occur. Devices on the network can communicate with each other to automate re-routing and switching to avoid power lines with faults, and detect and even repair faults in wires before they lead to outages.

Also introduces a new level of communication between the consumer and the power suppliers. The current interface between the suppliers and the customer is the meter, which has remained basically the same, technologically-speaking, for the past century, and cannot communicate information to or from the consumer. Smart grids, however, allow power companies and consumers to gather precise information about the quantity and timing of household consumption, and enable consumers to receive information, such as real-time pricing and emergency grid requests to lower energy consumption [40].

Smart grid improvements will also integrate with intermittent energy sources that pose a challenge to the current system, like wind and solar power. New technologies will encourage consumers to invest in distributed generation, or locally-generated power sources, such as solar panels on a home, to supplement their power needs [41]. Making such investments worthwhile to consumers also requires regulatory change to allow different pricing contracts. For example, a home could be powered by its own solar energy during the day, and the consumer could sell any extra energy produced by his or her panels back to the larger grid (this contract option is called net metering). The credit for the energy sold during the day may cover what the home uses that evening. Smart grids would also accommodate plug-in hybrid cars, allowing consumers to move away from petroleum-based transportation.

Despite all of the benefits offered by smart grids, such a dramatic change in technology and approach will not be immediately adopted by industry or by regulators. Pilot projects, are important opportunities for researchers and regulators to learn about the potential effects of smart grid technologies [42].

The Smart Grid Technologies that are proven efficient in reducing the growing energy needs of residential customers cannot be applicable for those of Industrial loads. The work conducted in the thesis, that is a part of more comprehensive study in the University of New Orleans Power and Energy Research Laboratory (PERL), proposes a way on how smart grid can benefit the Industrial customers.

Characteristic	**Today's Grid**	**Smart Grid**
Enables active participation by consumers.	Consumers are uninformed and non- participative with power system.	Informed, involved and active consumers – demand response and distributed energy resources.
Accommodates all generation and storage options.	Dominated by central generation – many obstacles for distributed energy resources interconnection.	Many distributed energy resources with plug and play convenience focus on renewable.
Enables new products, services, and markets.	Limited wholesale markets, not well integrated – limited opportunities for consumers.	Mature wholesale markets, growth of new electricity markets for consumers.
Provides power quality for the digital economy.	Focus on outages – slow response to power quality issues.	Power quality is a priority with a variety of quality/price options – rapid resolution of issues.

Optimizes asset utilization and operate efficiently.	Little integration of operational data with asset management – business process.	Greatly expanded data acquisition of grid parameters – focus on prevention minimizing impact to consumers.
Anticipates & responds to system disturbances (self-heals).	Responds to prevent further damage – focus is on protecting assets following faults.	Automatically detects and responds to problems – focus on prevention, minimizing impact to consumer.
Operates resiliently against attack and natural disaster.	Vulnerable to malicious acts of vandalism and natural disasters.	Resilient to attack and natural disasters with rapid restoration capabilities

Table 2 Differences between the present grid and the smart grid

Smart grid technologies allow us to manage energy usage and save money by giving the liberty to choose when and how to use our electricity. It is this feature of the technology that allows us to optimize the integrated demand-supply chain use of electricity. A year-long study by the U.S. Department of Energy showed that real-time pricing information provided by the smart meter help consumers reduce their electricity costs 10% on average and 15% on peak consumption.

4.4 Evolution rather than Substitution

In "Diffusion of Innovations"[43] is described how diffusion of innovation usually takes the form of an S-shaped curve, as depicted in Figure 22. Innovations do not evolve on their own, but their diffusion may depend on interaction with existing practices and technologies. The S-curve represents the technological life cycle, from low diffusion in the early R&D discovery phase and pilot tests, to wider acceptance once the new technology is proven and produced at bigger scale and lower cost, to complete rollout and eventual substitution by other technologies. Various technologies may coexist and the diffusion of one technology may build on the basis of another technology.

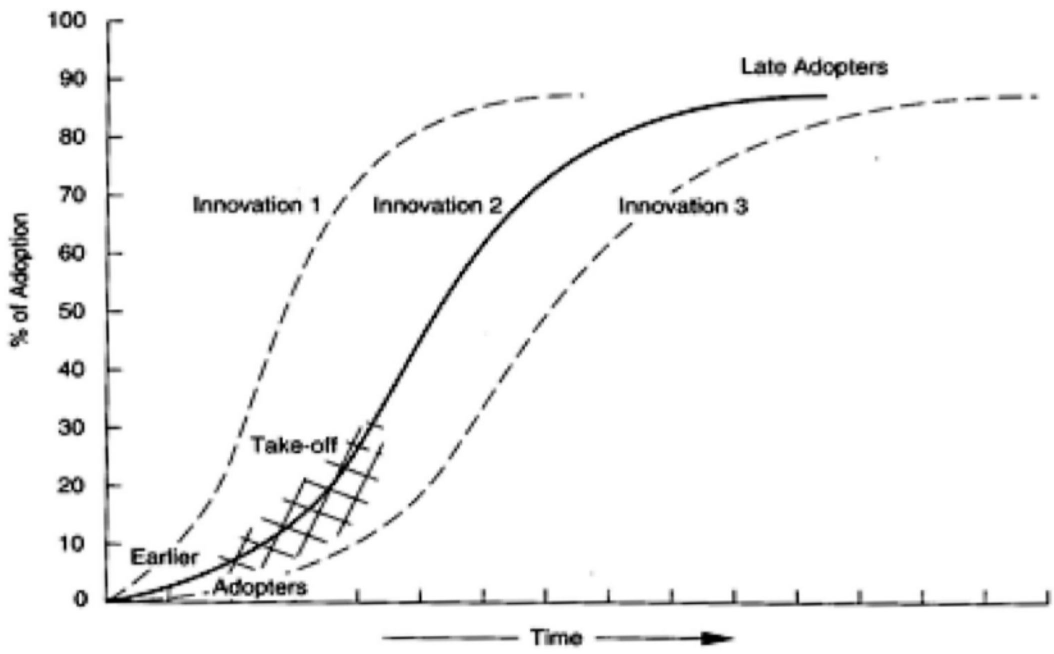

Figure 22 S-Model of diffusion of innovation [43]

Rather than a radical substitution of the old grid by a modern grid, the development of the smart grid should be seen as an evolution, the gradual 'smartening' of the existing grid by adding various new technologies (digital metering, communication, distributed renewable generation, advanced storage, electric vehicles, etc.) and applications (demand response, distribution automation, energy management systems, etc.) eventually leading to smart homes and smart grids. The diffusion of these technologies and applications is also expected to follow overlapping S-curves, as the penetration of one technology, such as smart metering, will enable the development and diffusion of the next technology, such as active demand or integration of micro-renewable power generation. Similarly, an electric vehicles (EV/PHEV) charging infrastructure will facilitate the diffusion of EV/PHEV and in turn enable storage capability through vehicle-to-grid (V2G) technology. Figure 23 shows how Italian utility Enel is planning the introduction of new technologies and applications on the road to a fully functioning Smart Grid [44].

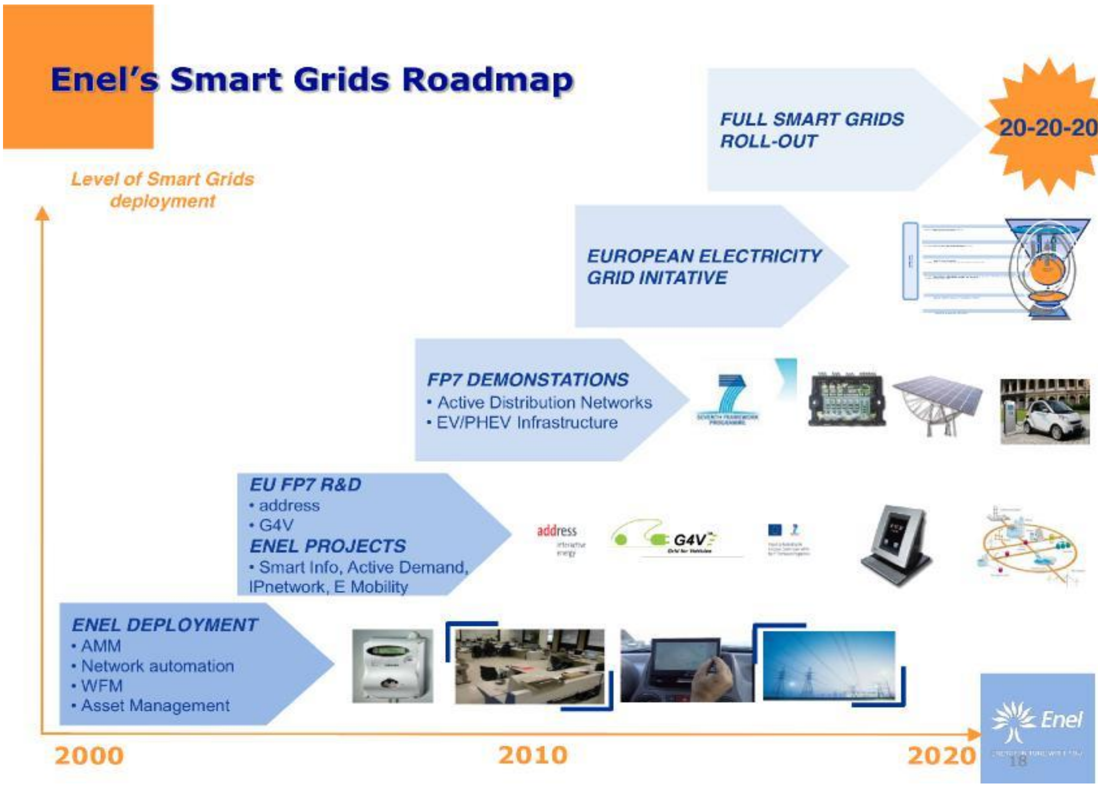

Figure 23 Enel's subsequent technological innovations on the way to full Smart Grid capability

4.5 The Components that Make up the Smart Grid

- **Electricity Supply Chain**

The electricity supply chain can be divided into 7 steps:

Figure 24 Smart electricity supply chain

A generation plant produces the electricity, which is transformed and transmitted by the transmission system operator (TSO) over high-voltage transmission lines. The TSO is responsible for balancing the supply and demand. From there, electricity is distributed by the distribution system operator (DSO) over medium or low voltage power lines to substations, where it is transformed again for final delivery. In the past, resellers and supply companies would buy electricity from the DSO and develop the commercial deals with end customers. Smart metering is allowing smart energy services companies to develop new business models and services dedicated to reduction of end user electricity consumption.

To stimulate competition, the EU Third Legislative Package in 2009 mandated unbundling of generation, transmission and distribution. The objective was for these steps in the value chain not to be owned by the same company, but only 15 of the 41 European transmission system operators (TSO) have been fully separated from electricity generation and retail (PWC, 2010). Only the UK, the Netherlands, Austria, Hungary, Poland and the Nordic region (with the exception of Denmark) have a reasonably open competitive environment. In the European states where the generation/transmission, distribution and retail of electricity is unbundled completely or to some extent, the customer is 'owned' by the electricity retailer [45], who in turn buys electricity from the network operator, who in turn is supplied by the generation/transmission company. The customer is free to change energy supplier at any time.

- **Physical, Communication and Application Layers**

To arrive to a fully intelligent grid, generation and communication of real-time data regarding demand, supply and network status are required throughout the grid. Management systems and applications are required to turn the data into operational and asset management decisions for the operators, as well as consumption decisions for end customers, thus increasing the efficiency of the whole value chain.

Until now, most utilities and grid operators have sensors, meters and data communication systems in place to monitor the transmission and some distribution parts of the grid, but very limited information is generated about the consumption patterns at the point of end- consumption. As an important step towards solving this data gap and stimulating transparency and competition in the electricity sector, the European Union set a 2020 deadline for an 80% rollout of smart meters with two-way communication and remote control capability, through Energy Services Directive 2006/32/EC (Art. 13) and the Directive on internal markets 2009/72/EC.

A fully-fledged smart grid normally incorporates the following components, shown in Figure 25:

- Advanced metering Infrastructure (AMI)
- Demand response (DR) systems
- Energy management services / Home automation networks (HAN)
- Distribution automation (DA)
- Distributed and renewable electricity generation (DG/RES)
- Advanced energy storage
- Electric vehicles (EVs) charging infrastructure
- Systems management and data security ICT

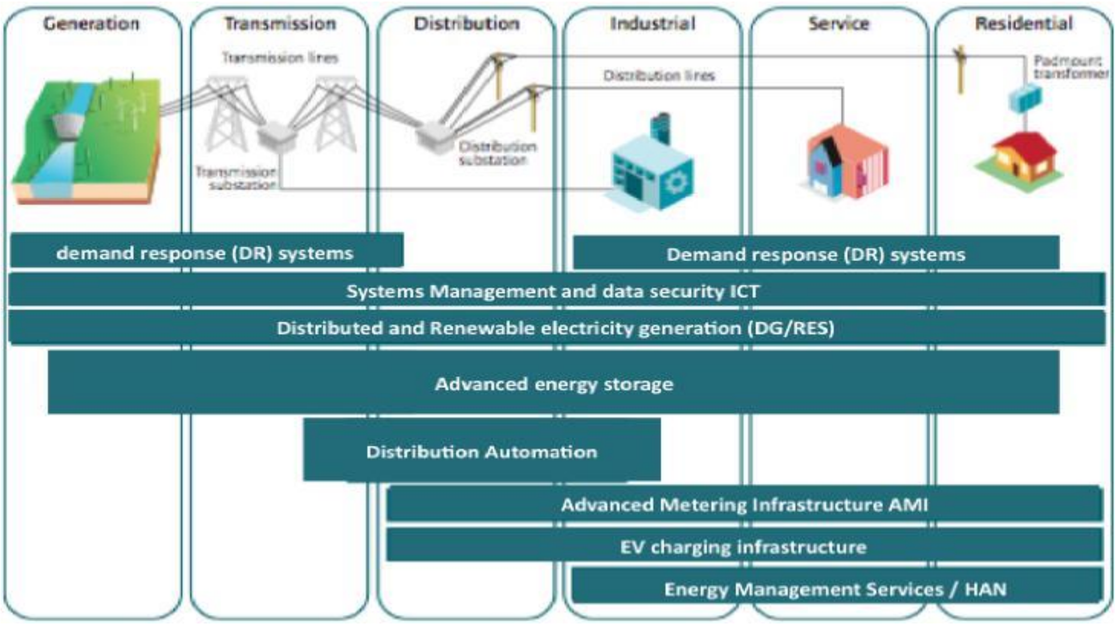

Figure 25 Electricity system and smart grid components [46]

4.6 Microgrid

A microgrid is a localized grouping of electricity generation, energy storage, and loads that normally operates connected to a traditional centralized grid (macrogrid). This single point of common coupling with the macrogrid can be disconnected. The microgrid can then function autonomously. Generation and loads are usually interconnected at low voltage. From the point of view of the grid operator, a connected microgrid can be controlled as if it was one entity. Microgrid generation resources can include fuel cells, wind, solar, or other energy sources. The multiple dispersed generation sources and ability to isolate it from a larger network would provide highly reliable electric power. By-product heat from generation sources such as microturbines could be used for local process heating or space heating, allowing flexible trade-off between the needs for heat and electric power [47].

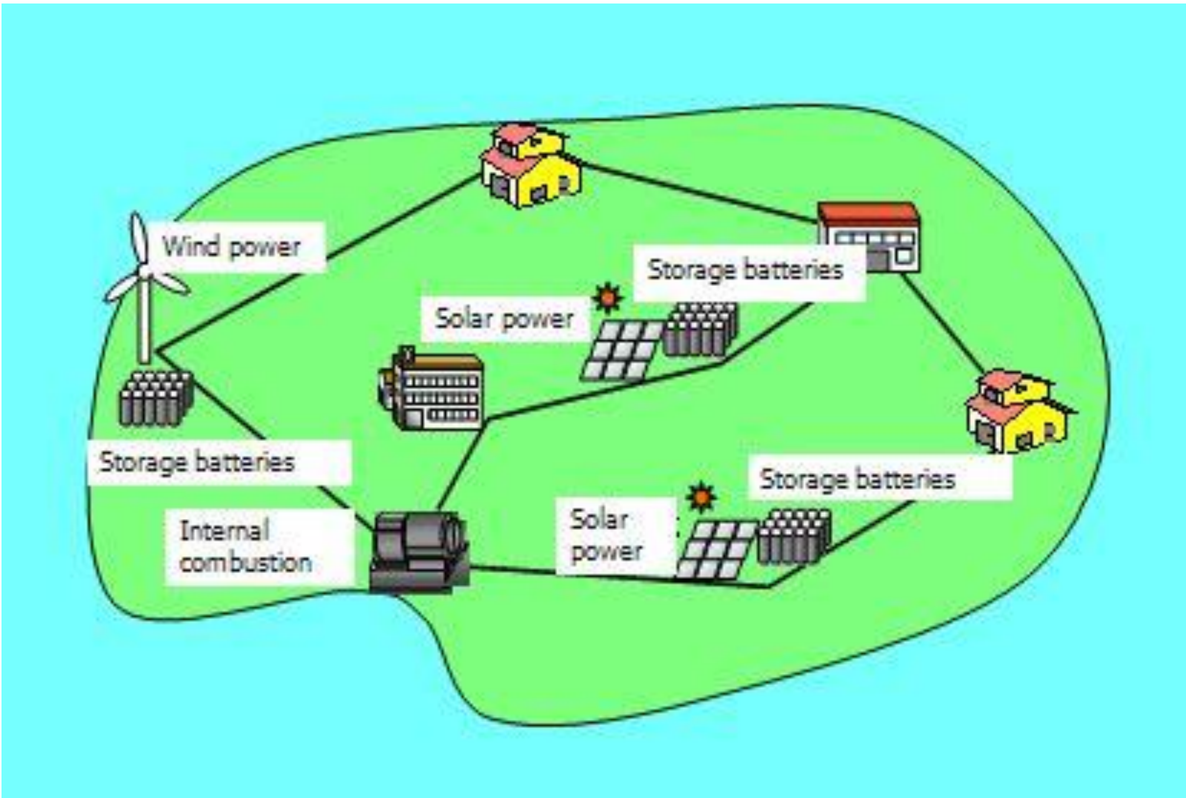

Figure 26 Microgrid [48]

5. Energy Storage Technologies

5.1 The Concept of Energy Storage

Increasing amount of research in the field of ES technologies, and the eager to find new solutions has several reasons. Concepts like hybrid vehicles and eco-friendly transport, smart grids and more efficient exploitation of renewables, are all important aspects affecting the effort put into this R&D process. There are numerous solutions that have proved or seem to have a potential within ES, supported by theory, experience and test plants, and several are already introduced and established on the market.

Today there is a global installed storage capacity of 100GW, of which 99% is represented by pumped hydro [49]. Extensive, on-going R&D is trying to find new and efficient solutions for ES. Predictions say that the amount of electrical energy produced will increase from 12% of the total global energy production in 2007 to 34% in 2025, where the share of RE will also rise. Hence, the need of more installed ES capacity is obvious [50] .

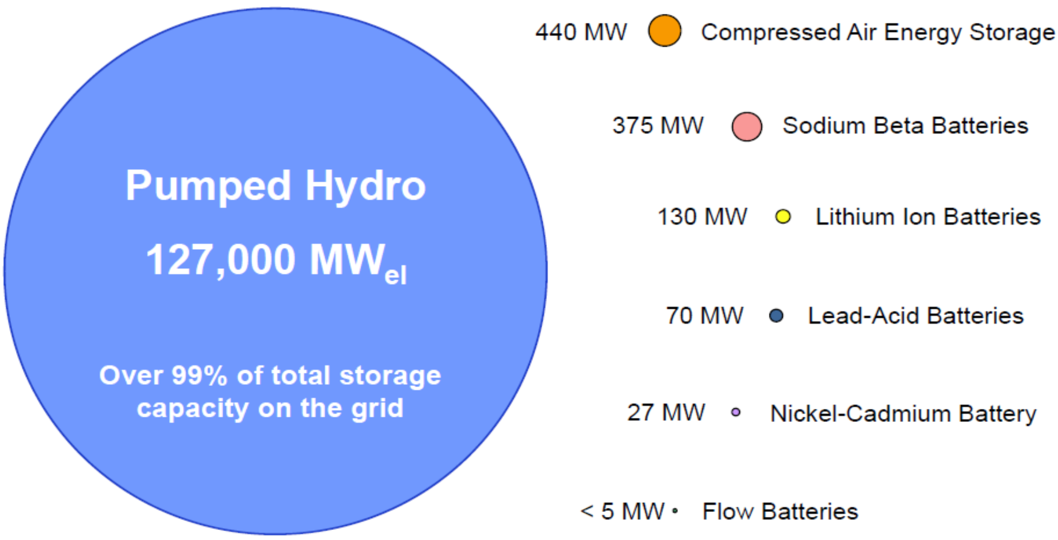

Figure 27 Storage capacity for electrical energy [51].

For large-scale integration of RE, its intermittent characteristic makes incorporation onto the electric grid more challenging. New and better technologies are required, to provide possibilities for control and regulation of the electricity generation, in addition to a general improvement of grid stability and reliability. This is why ES has become more important the last decades, as the energy market experience changes in favour of renewables. It allows these intermittent resources to "provide energy when it is needed, just as transmission provides energy where it is needed" [52], despite their stochastic power production. Due to high costs and technological barriers, conventional and reliable methods for power generation like fossil fuel are still preferred, but this seems to be heading for a new course.

There are several applications for which ES can be used, as illustrated in Figure 28. These have generally been divided into five broad application categories: generation related, ancillary services, transmission and distribution (T&D), end-user and renewable integration [53]. In this thesis the main issue will be integration of renewables, as introduced in chapter 0, which requires somewhat large-scale ES (mostly in the range of MW). This is a very important ES application, as this principle is *"best thought of as enabling technologies..(....)..promoting a market change, such as the faster introduction of renewable energy resources. [54]*

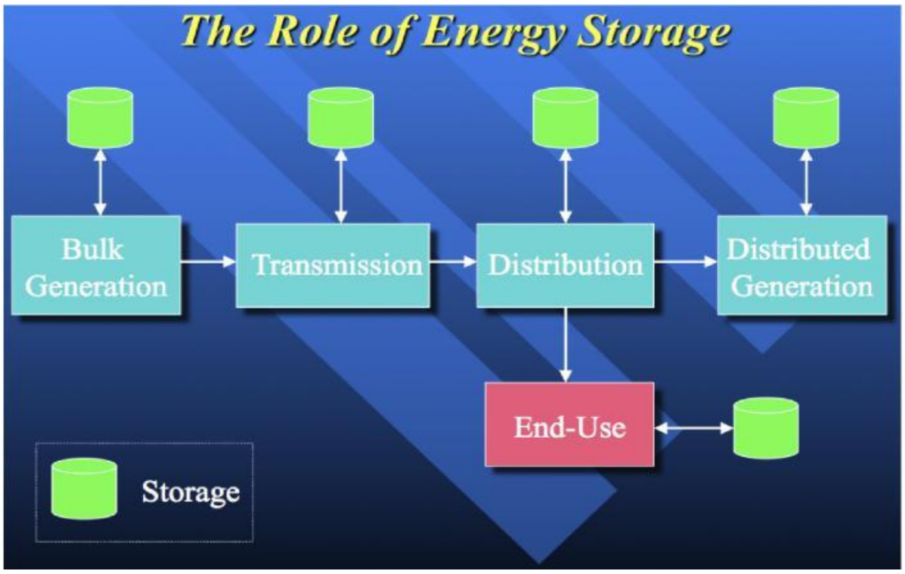

Figure 28 Roles of energy storage [55].

Working on integration of renewables, ES could be used for several applications: match supply and demand, store surplus electricity generated on the plant, act as an electricity backup when generation is not available, and smooth output fluctuations from the intermittent energy resources [56].

Figure 29 shows a simple structure of an ES system. With a controller monitoring the deviation of electricity demand compared to production, it can regulate the electricity output necessary from the storage device (discharge). If the demand falls below the production level, the storage unit will be charged.

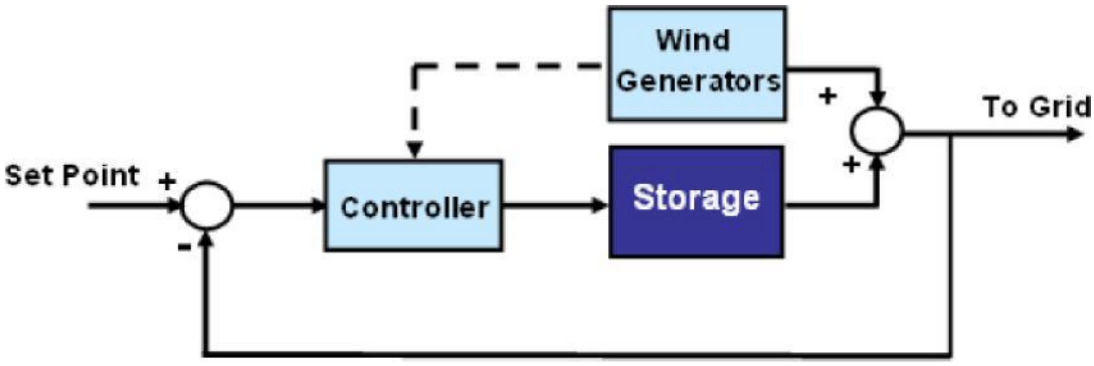

Figure 29 Structure of an ES system [57]

Several technologies can contribute to serve the applications mentioned. Some of the general characteristics and their ideal values of ES systems are defined as SERG[55].

- Quantity of energy stored (commonly kWh or MWh)
- Duration of discharge required (seconds, minutes, hours) → scalable
- Power level (kW or MW) →high power
- Response time (milliseconds to minutes) →fast dynamic response, flexible
- Frequency of discharge (number per unit of time, such as per day or year)
- Energy density (facility space and total ES capacity) →high energy density
- Cycle Efficiency (fraction of energy returned to the grid) →high conversion efficiency
- Cycle life → long lasting
- Footprint/compatibility with existing infrastructure →easy to integrate and implement

- Transportability →relocatable
- Cost → cheap

Considering these characteristics, they all in a varying degree describe the technologies introduced in Chapter 5 . The criterions from which ES is to be assessed in this thesis comprise the characteristics of cheap, flexible, scalable and high energy densities. All ES technologies have strengths and weaknesses, and it is important to choose the one best suited for a few related applications, where its technical capabilities can be leveraged for maximum economic benefit [54].

Enabling renewables to be integrated into energy market has a high priority on the ES agenda “EPRI 2008” [57], with the objective to solve the following problem of intermittency. For adequate ES capacity available, system planner need to include sufficient generating capacity to meet average demand rather than peak demands [58].

The basic principle of ES is to charge the storage device using off-peak and/or excess renewable electricity, and discharge through electricity production in periods of peak demand and high electricity price. How this cycle function is defined by the ES

characteristics of the different technologies. The essential characteristics, which determines the cost of an ES facility, are [49]:

- Storage properties: energy density, output density, energy storage efficiency, storage scale and charge/discharge times.
- Operation properties: start/ stop times, load response, partial load feature, lifetime, reliability.
- Surroundings/ circumstances: Location, construction time, safety and lead time/ market development.

The significance of the above characteristics is decided by the scope of the project and storage application. Figure 30 shows the distribution of the most common ES technologies based on the essential characteristics of discharge time and power rating.

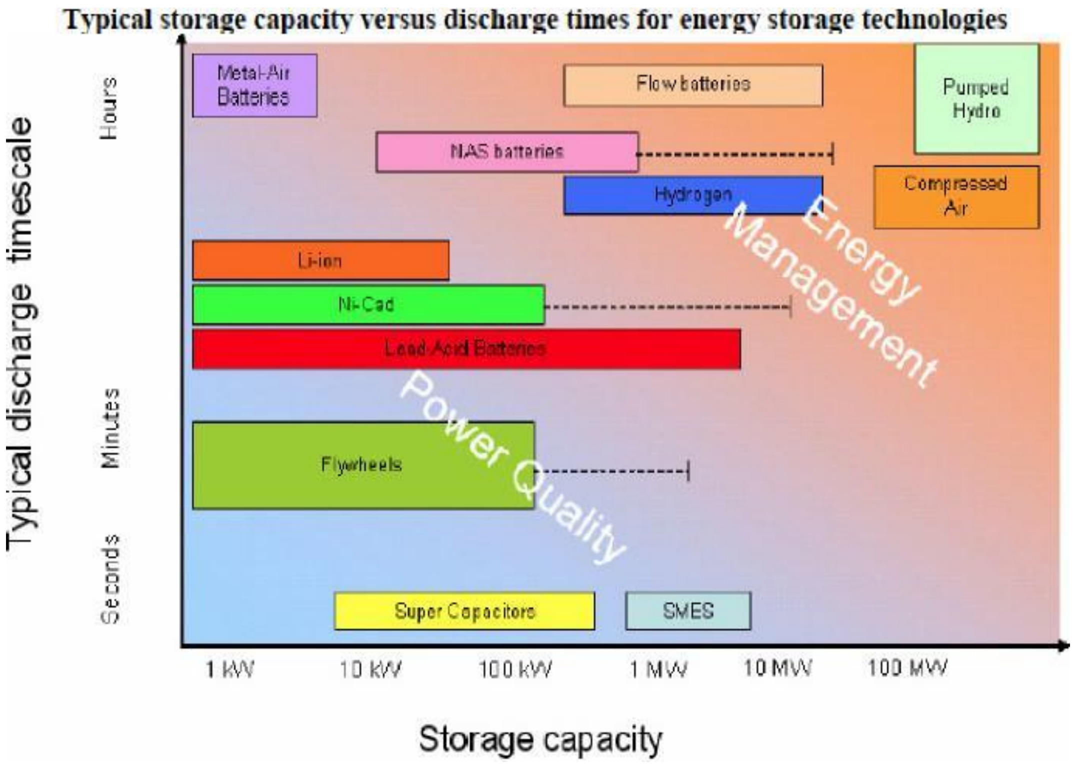

Figure 30 Storage capacity versus discharge time for ES technologies [59].

5.2 The Need for Energy Storage in the Future Grid

Indeed, ES is an established, valuable approach for improving the reliability and overall use of the entire power system (generation, transmission, and distribution [T&D]). Sited at various T&D stages, ES can be employed for providing many grid services, including a set of ancillary services such as:

- Frequency regulation and load following (aggregated term often used is balancing services)
- Cold start services.
- Contingency reserves.
- Energy services that shift generation from peak to off-peak periods.

In addition, it can provide services to solve more localized power quality issues and reactive power support.

Balancing services are used to balance generation and demand in tightly limited situations to maintain the alternating current (AC) system frequency of 50/60 Hz. ES is perfectly suited to provide this service by absorbing electric energy (charging cycle) whenever there is too much generation for a given demand and by injecting electric energy into the power grid (discharging cycle) when there is too little generation. Traditionally, these services have been performed by conventional gas or steam turbine technologies. But rather than varying the torque of large rotary turbo-machinery on a second-by-second basis, electrochemical ES is much better suited to quickly respond to the grid needs. To operate the electric grid reliably requires contingency reserves that are used in cases of a grid contingency such as an unplanned outage of a power plant or transmission line. Various kinds of contingency reserves are necessary to step in when the contingency occurs. Reserves are classified by how quickly they can be brought online and how fast they respond to a grid contingency the faster the response, the sooner the contingency can be managed. A recent analysis suggested a relationship between contingency reserve capacity requirements and reserve response time—the faster a grid asset responds, the less capacity the system needs.[11] This result suggests that a fast-responding ES unit may potentially provide a higher value to the grid than a conventional turbine unit of the same capacity size (MW). Furthermore, in addition to providing reliability service to the grid, ES can improve the economic efficiency of the electricity infrastructure by improving its utilization. On average, the entire electricity delivery system (T&D) is used to about 50%.12 Designed for a peak load condition with some reserve margin and load-growth expectations added to the peak load, the infrastructure is underused most of the time. From an economic efficiency point of view, this is less than optimal. To improve the entire use of the grid assets, the system will need to be more evenly loaded. ES can play an important role in that process by shifting electric energy from peak to off-peak periods. As shown in Figure 3, electrical energy is stored (via load levelling) when it can be produced cheaply (at off-peak times, for example) and released at peak times when it is more valuable.

To date, however, ES (almost exclusively pumped hydroelectric storage) contributes to only about 2% of the installed generation capacity in the United States. The percentages are higher in Europe and Japan, at 10% and 15%, respectively, largely because of favourable economics and government policies.[13] With little energy storage capability, the U.S. power grid has evolved by relying on redundant generation and transmission grid assets to meet the grid reliability requirements. While this power system design concept has provided grid operations with acceptable levels of reliability in the past, the future grid will face significant challenges by providing clean power from intermittent resources to a much more dynamic load. These challenges will not only be faced in the United States, but also internationally. With the general effort by many nations to lower their national carbon footprint, a greater reliance will be placed on the nation's electric power grids as their energy system backbone. With tighter constraints on carbon emissions, a general trend of electrification of fossil-fuel-based end uses is emerging. The most prominent is the electrification of transportation. Some estimates suggest that 30-50% of all new vehicle purchases in 2030 will be plug-in hybrid vehicles. Other services, such as residential heating, which is generally provided by fuel oil and natural gas, may be electrified with tighter emission constraints. This places an increasingly growing importance and reliance on the power grids to support the nations' economies. But not only will the demand for electricity grow, the way the electricity is being used will also become much more dynamic as residential, commercial, and industrial electricity customers install onsite generators (such as PVs, fuel cell technologies, and other distributed generators) and become net producers of electricity at certain times. On the large scale power generation side, a significant new capacity of intermittent renewable energy is projected to decarbonize the electric power system.

While the absolute capacity of intermittent renewable energy resources that can be integrated into the existing power grids may vary from region to region, there is ample consensus that additional flexible grid assets are required to accommodate the increasing variability in power production. A doubling of the regulation service requirements to maintain 60 Hz grid frequency and safe grid operations has been reported to be necessary for California and the Pacific Northwest by 2020. California will then have a contribution of renewable energy resources to the entire generation mix of 30%. The Pacific Northwest is estimated to have between 15 and 20% of electricity from renewable, non-hydro resources. At a national level, the U.S.

Department of Energy (DOE) targets a 20% contribution of renewable energy to the total electric generation mix.

To meet this target would require about 300 GW of new capacity. The majority of this new capacity is likely to be wind and solar resources because of their technological maturity and economic characteristics. To integrate new wind and solar energy resources at this scale, significant investments will be required to upgrade the grid. And the need of grid investment is already felt. On February 26, 2008, a cold front moved through west Texas, and winds died in the evening just as electricity demand was peaking. Over a 2h period the generation from wind power in the region plummeted rapidly from 1.7 GW to only 300 MW, while the power demand rose to a peak of 35612 MW from 31200 MW. The sudden loss of wind power and the lack of alternative electricity supply to ramp up as quickly forced the Electric Reliability Council of Texas (ERCOT) to curtail 1100 MW demand from industrial customers within 10 min and grid stability was restored within 3 h. To prevent a similar problem, ERCOT investigated the addition of ES. As a result, in April 2010 Electric Transmission Texas (ETT) installed a 4 MW sodium-sulphur utility scale battery system in Presidio, TX. ES will not only function as a buffer for the intermittency of renewable energy resources but also as a transmission resource if placed properly in the grid. As mentioned above, there are many other grid services that ES can provide to the grid, and several of them can be provided simultaneously. While ES can provide significant value to the grid today in the United States and internationally, it should be noted that other conventional and nonconventional technologies will compete for the same market share. For ES to be successful, it will need to compete on its own merits. Its cost and performance characteristics will need to be cost competitive with the conventional technologies. In most cases, this is a natural gas combustion turbine. However, with the significant national and international investments in smart grid technologies, demand response or load side control strategies are emerging as a new technology to offer some of the values that ES competes for. The U.S. Congress has recognized the potential of ES as an enabler for fully used smart grid technologies to integrate a large capacity of renewable energy resources in the Energy Independence and

Security Act of 2007. This legislation authorized DOE to develop and demonstrate storage technologies for utility applications. The American Recovery and Reinvestment Act of 2009 has made a significantly level of funding available for stationary energy storage demonstrations. Additionally, commercial interests have been generated to develop stationary energy storage technologies for utility applications. Several pilot projects are under way to test the performance and reliability of ES. Recently, California enacted a law requiring utilities to include energy storage systems in electricity distribution networks that can handle 2.25-5.00% of peak load. While ES may already be cost competitive for some high-value niche markets, further cost reduction has to occur for ES to be more widely used. DOE is the key U.S. funding organization to address the science and technology research needs for the next generation of storage materials and storage systems [60].

5.3 Stationary Applications

- **Transmission Support**

  In this application, the battery system provides pulses of real and reactive power to stabilize transmission lines. The battery must be of sufficient size to support transmission assets, which implies 10s to 100s of megawatts. Since this is a pulse power application, and the pulses are somewhat infrequent, not much storage capacity is required, and the life of the batteries would primarily be determined by calendar life limitations. The first pulse may be discharge or charge, depending on the cause and nature of the particular de-stabilizing event, so the battery must be maintained at an intermediate state of charge.

  The electricity storage system allows transmission lines in a constricted network to be more heavily loaded during periods of peak demand by customers. This allows utilities to defer investments in transmission assets [61].

- **Area Regulation & Spinning Reserve**

These ancillary services are typically provided by generating assets operating at zero or partial loading. A battery system can provide load following (real and possibly reactive power) for area regulation (frequency regulation for an island system) and provide an alternative method for short term, fast response spinning reserve. As in transmission support, the first use for area regulation may be discharge or charge, so the battery must be maintained at a partial state of charge.

This set of applications requires a fairly strenuous duty cycle. Spinning reserve requires 15 minutes at full power and 15 minutes of ramp down from full power to zero. These events only happen about once a month, but they would require a complete discharge of the battery. Area regulation requires zero net unscheduled power flow between control areas in each 15 minute period. The energy transferred to meet this application is only about 25% of that for spinning reserve, but the battery is cycled continuously.

The benefit of the electricity storage system in both spinning reserve and area regulation derives from reducing or eliminating the fuel and maintenance costs that are normally associated with underutilized generating assets. The benefit derived from area regulation is probably inadequate to justify a battery, but once an electricity storage system has been installed, a battery could be the least cost alternative for this service [62].

- **Load Leveling/Energy Arbitrage/Transmission Deferral**

This is the classic utility application for energy storage: store cheap electricity generated off peak and sell it on-peak when more expensive generators are required. Alternatively, the use of night-time electricity on-peak can allow deferral of transmission expansions.

This application requires large storage capacities, with discharges of five hours or more favoured by most utilities, particularly for transmission deferral and arbitrage. Each discharge removes most of the capacity of the battery, and discharges would occur every weekday when power use is high, i.e., 100 to 200 days per year.

The benefit of the electricity storage system in this application is the difference between the cost for supplying electricity close to the loads from on-peak generation and transmission assets and the cost for supplying electricity from off peak assets [63].

- **Renewables Firming**

Most renewable energy resources, such as wind and solar energy, are intermittent in nature, they do not provide a reliable, continuous source of power. This limitation prevents system operators from having the same type of control over renewable generating assets that they have over other generating assets. For this reason, prices paid for electricity generated by renewables (unfirm power) are typically lower than what is paid for firm power.

An energy storage system can follow the renewable generation (and to a lesser extent the system load) and allow the renewable generator to be counted a firm resource. This application requires a wide range of storage capacities, depending on the nature of the renewable resource and the presence or absence of other generators that fill in the gaps. The duty cycle for this application depends on the nature of the renewable resource, but would probably be similar to that found in the other load following applications, with many shallow DOD cycles superimposed on daily deep discharges. The first event after a period of inactivity may be discharge or charge, depending on the needs of the electric system and the renewable resource.

The benefit of the electricity storage system for renewables is the extra revenue for firm electricity as compared to electricity from a non-firm resource. Additionally, variations in the power from renewables can cause problems with transmission, since wind and solar farms are often placed remote from loads and are often connected through weak lines. The benefit estimates used here are derived from avoided transmission upgrades [63].

- **Power Reliability & Peak Shaving**

An energy storage system can provide electricity during extended outages and reduce the purchase cost for electricity (demand charges, time-of-day prices) by shaving peaks. The second use of EV batteries for Uninterruptible Power Source (UPS) applications alone appears very unlikely, given the low cost of lead acid batteries for these applications and the fact that they are widely used and have well-defined warranties. Thus, peak shaving must be used together with the power reliability function. In this case, the customer will have to decide on the value of the system for each application and then decide how much capacity to hold back for power reliability.

Battery systems designed to meet this application could be as large as 2 MW in rated power output, but will most likely consist of 100 kW modules. Three to four hours of storage will be required to provide blackout ride-through and significant peak shaving benefits. Blackouts may only occur a few times per year, but peak shaving could be used almost every workday depending on the electricity tariff for the site.

The benefit of the electricity storage system in this application is mostly in the power reliability function, with peak shaving being used to offset the total costs of the system.

- **Light Commercial Load Following**

A battery will likely be used in tandem with most distributed generation technologies (including renewables) to allow more efficient and more reliable operation. The battery system would be used for load-following, thereby allowing a generator to run at relatively constant power delivery or a renewable resource to better match the load. This mode of operation would require the battery to be in use (charge or discharge) most of the time, and it would be at a partial state of charge for much of the time.

The benefit of the electricity storage system in these applications is in allowing more efficient and more dispatchable local generation. Battery systems would only be practical for these applications if a utility connection were not economically viable, if a battery system owner could arrange to receive a high price for any excess electricity that could be sold back to the utility, or if the battery reduces the cost of the distributed generating system by avoiding the need for an oversized generator to meet peak loads.

- **Distributed Node Telecom Backup Power**

  Lead-acid batteries already provide power for distributed nodes (fiber nodes) of the telecomm system during electric utility outages. The replacement of lead acid batteries for telecom .switches. is deemed very unlikely, but lithium-ion batteries are already being supplied in test quantities for the distributed telecom node application. Very high reliability, i.e., the ability to deliver the stated capacity and power, is a must for this application (in order to minimize costly service calls). Since the batteries are used for backup power, the duty cycle in this application is fairly benign. However, VRLAs used in this application have shown lifetimes as short as one year due to the acceleration of aging processes by the high temperatures frequently encountered in telecom equipment boxes. Advanced battery technologies may show less performance degradation during high temperature float or standby compared to lead acid batteries, resulting in longer battery lifetimes.

  The benefit of an alternative to lead-acid batteries in this application is in lower life cycle costs due to longer time between replacements. The benefit estimates listed above are based on the current price for VRLAs.

- **Residential Load Following**

  This application is very similar to light commercial load following, just on a smaller scale and operating under different load profiles. Distributed generation technologies for residential use will likely be paired with a battery system to improve their efficiency and reliability. The benefit of the electricity storage system in these applications is in allowing more efficient and more dispatchable local generation. Battery systems would only be practical for these applications if a utility connection were not economically viable, if a battery system owner can arrange to receive a high price for any excess electricity that can be sold back to the utility, or if the battery reduces the cost of the distributed generating system by avoiding the need for an oversized generator to meet peak loads.

5.4 Main Electrochemical Storage Technologies

Energy can be stored in electrical, mechanical, electro-chemical, chemical and thermal means, delivering the final energy in electrical form. (See Table 3.)

Type	**Sub-group**	**Examples (not exhaustive)**	**Typical Applications**
Electrical	Capacitors	Capacitors and ultracapacitors.	Power quality
	Superconductors	Superconducting Magnetic Energy Storage (SMES)	Power quality, reliability
Mechanical	Potential energy in storage medium	Pumped hydro,	Energy management, reserve
		Compressed air energy storage (CAES)	Energy management, reserve
	Kinetic energy in storage medium	Low-speed flywheels	Uninterruptible power supply
		Advanced flywheels	Power quality
Electro-chemical	Low-temperature batteries	Lead-acid	Power quality,
		Nickel-cadmium	Power quality
		Lithium cells	Power quality

	High-temperature batteries	Sodium-sulphur	Multi-functional
		Sodium-nickel chloride	Standby power, remote area
	Flow batteries	Zinc-bromine	Multi-functional
		Vanadium	Remote area applications
		Polysulphide-bromine	Multi-functional
		Cerium-zinc	- -
Chemical	Hydrogen cycle	Electrolyser/ fuel cell combination	- -
	Other storage media	*e.g.* chemical hydrides	- -
Thermal	Hot water	- -	Peak shaving
	Ceramics	- -	Peak shaving
	Molten salt/ steam	- -	Integration of
	Ice	- -	Peak shaving

Table 3 Storage Type Grouped by Technology [64].

The main electrochemical storage technologies are described below:

- **Lead-acid battery**

  Lead acid battery technology is one of the oldest and most developed battery technologies. They come in two basic forms: flooded lead acid batteries, which are considered a well proven and robust design, and valve regulated lead acid (VRLA, or “maintenance free batteries”) batteries. These batteries are also used in traction for lifts, golf carts, UPS, mines etc. Lead-acid batteries have some known drawbacks and limitations. They are heavy giving rise to very poor energy to weight and power to weight ratios that limit their applications. The lead content and the sulphuric acid electrolyte make the battery environmentally unfriendly (although approximately 98% 23 of lead acid batteries are recycled). They have short cycle life and long recharge times. They can only accommodate a small number of full (“deep”) discharges and cannot be stored in a discharged condition without service life failure.

Relatively low self-discharge rate of lead acid batteries makes them a common choice for standby stationary energy storage such as uninterruptible power supplies (UPS). Lead acid batteries have been used for utility applications such as peak shaving. However, the economics and life cycle requirements do not work out well for the lead acid batteries. They are therefore not the dominant provider of Stationery Utility Energy Storage (SUES) applications. Their popularity is expected to decline as advances in other technologies occur with the exception of SLI applications.

- **Nickel Based Batteries**

There are two types of nickel batteries, the older, nickel-cadmium (NiCd) batteries, and the newer, nickel metal hydride (NiMH) batteries, both are rechargeable.

- **Nickel-Cadmium (NiCd) Batteries**

  These batteries use nickel oxy-hydroxide and metallic cadmium as the electrodes. They come in two designs: sealed and vented. NiCd are relatively inexpensive, able to sustain deep discharge, recharge quickly, and have a long cycle life. NiCd can also endure very high discharge rates with no damage or loss of capacity. Hence they are common among power tools.

  However, NiCd are extremely environmentally unfriendly because of the use of toxic cadmium. They have relatively low energy density and relatively high self-discharge rates, which require recharge after relatively short storage periods. The charging rates are very sensitive to hot and cold temperature conditions. There are also known memory effects that shorten the battery shelf life. They compare unfavourably in terms of availability and energy density with the Nickel Metal Hydride (NiMH) and Li-ion batteries.

There have been a few demonstrations of large scale SUES applications, such as the system installed by the Golden Valley Electric Association Inc. (GVEA) in Fairbanks, Alaska. The system consists of 13,760 cells and could provide 40 MW of power for up to seven minutes. However, the inherent disadvantages of Ni-Cd relative to other emerging battery technologies and environmental considerations have largely relegated the Ni-Cd battery to the backburner. There is little, if any anticipated growth for Ni-Cd in SUES applications.

However, Ni-Cd are extremely environmentally unfriendly because of the use of toxic cadmium. They have relatively low energy density and relatively high self-discharge rates, which require recharge after relatively short storage periods. The charging rates are very sensitive to hot and cold temperature conditions. There are also known memory effects that shorten the battery shelf life. They compare unfavourably in terms of availability and energy density with the Nickel Metal Hydride (NiMH) and Li-ion batteries.

- **Nickel Metal-Hydride (NiMH) Batteries**

These are another alkaline Nickel-based battery technology that has replaced Ni-Cd in many applications. NiMH batteries provide 30 to 40% more energy capacity and power capabilities compared to the same size Ni-Cd cell. NiMH is able to meet the high power requirements in hybrid electric vehicles (HEV); and as such has been the dominant battery technology powering today's HEV such as the Toyota Prius. NiMH are considerably more environmentally friendly compared with lead acid and Ni-Cd batteries. They can be charged in about 3 hours, although, like Ni-Cd, charging rates are sensitive to both hot and cold temperature conditions. While NiMH batteries are capable of high power discharge, consistent use in high-current conditions can limit the battery's life.

The NiMH's self-discharge 25 rate is quite high, up to 400% greater than that of a lead-air battery . The most significant operational challenge with NiMH relates to recharge safety. The temperature and internal pressure of a NiMH battery cell rises significantly as it reaches 100% state of charge. To prevent thermal runaway, complex cell monitoring electronics and sophisticated charging algorithms must be designed into the battery system. With NiMH technology gaining prominence in the electric and hybrid electric vehicle markets industry participants believe there are looming pressures on nickel supplies, which is one significant factor that may limit the technologies ability to scale.

The general sense among the industry is that other technologies offer a more favourable energy density and cost profile for utility-scale energy storage applications.

- **Redox Flow Batteries**
  - **Zinc-bromine Flow Battery**

It is a type of hybrid flow battery with nominal cell voltage 1.8 V and energy density 16–39 W·h/L or 34–54 W·h/kg. (See Figure 31) The battery systems have the potential to provide energy storage solutions at a lower overall cost than other energy storage systems such as lead-acid, vanadium redox, sodium sulphur, lithium-ion and others.

Figure 31 RedFlow ZBM zinc-bromine battery: 5kWh and 10kWh.

- **Vanadium redox-flow battery (VRB)**

  It is one of the mostly studied rechargeable flow batteries, in which only one electroactive element vanadium in four different oxidation states is used. The open circuit voltage of VRB is 1.41 V and energy density 25 Wh/kg. The extremely large capacities possible from vanadium redox batteries make them well suited to use in large power storage applications.

  It can be recharged simply by replacing the electrolyte if no power source is available to charge it. The main disadvantages with vanadium redox technology are a relatively poor energy to volume ratio, and the system complexity in comparison with standard storage batteries. Large systems with power of 200kW - 1.5 MW have been installed.

- **Li-ion Batteries**

Li-ion batteries, the most successful electrochemical devices were first commercialized in 1990 based on the extensive knowledge gained in intercalation chemistry by inorganic and solid state chemists during the

1970’s to 1980’s. The first generation of such batteries allowed storing more than twice the energy compared to nickel or lead batteries of the same size and mass. Today, the Lithium ion batteries offer the promise of high energy, high power, high efficiency, longer life, and easier state-of-charge control at lower weight, volume, and reasonable cost.

Commercially available Li-ion batteries ($LiCoO_2$ versus graphite) have many advantages, high open circuit voltage (4V), excellent cyclic performance and highly reversible (>99% coulombic efficiency), but limited lithium storage capacity. However, both existing and new emerging applications demand even better performance in terms of energy density, power, safety, price and environmental impact. As a consequence, there is a great interest to increase the storage capacity of both the cathode as well as anode materials of Li-ion battery. See Figure 32 on the schematic of a Li-ion battery.

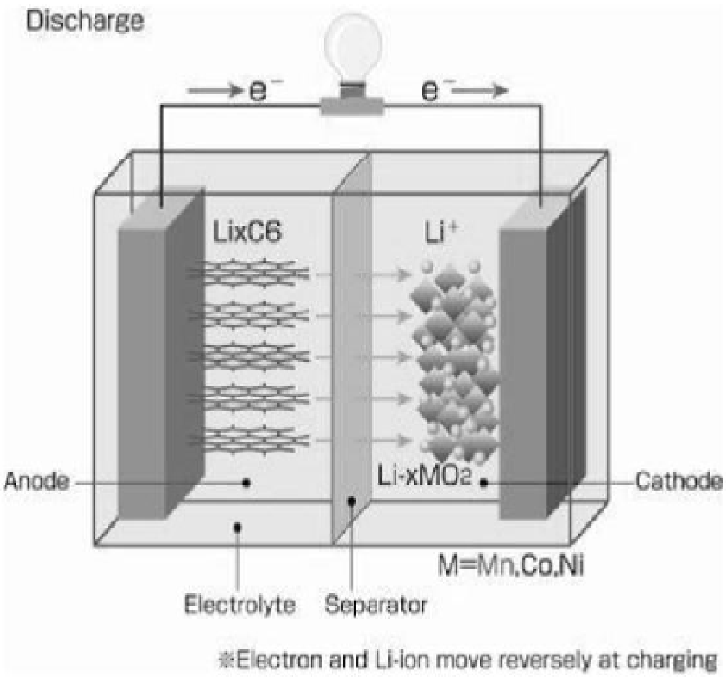

Figure 32 Schematic of a Lithium Ion Battery

Among the existing cathodes used in Li-ion batteries, phosphate based cathode ($LiFePO_4$) offers high rate performance, excellent cyclability, relatively safe operation and low cost. However, combining $LiFePO_4$ with conventional graphitic anode in a full cell poses serious limitation for fast charging and subsequent safety of the system. Thus there is a need to look for anode materials that operate at slightly higher potential for safety reasons. Lithium titanate ($Li_4Ti_5O_{12}$) and titania (TiO_2) are being considered as high potential anode materials with negligible volume expansion and very high cyclic performance (15,000 cycles compared to graphite having 5,000 cycles).

- **Metal-air Batteries**

Metal-air batteries are the most compact and, potentially, the least expensive batteries available and are environmentally benign. The anodes in these batteries are commonly available metals with high energy density like aluminium or zinc that release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good OH^- ion conductor such as KOH. The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH. The main disadvantage is that electrical recharging of these batteries is very difficult and inefficient [65].

- **Zinc-air Batteries**

Zinc-air batteries are electro-chemical batteries powered by oxidizing zinc with oxygen from air. Zinc air delivers the highest energy density of any commercially available battery system, and at a lower operating cost. This advantage is due to the use of atmospheric oxygen as the cathode reactant. It allows more zinc to be used to fill the zinc-air cell. Typically, batteries contain approximately the same amount of anode and cathode material, thus their service life is limited by the material that is consumed first. Thus, the increase in amount of anode material of the zinc air battery offers up to 5 times more capacity(gravimetric energy density of up to 442 Wh/kg, volumetric energy density of up to 1673 Wh/l) than regular zinc-anode systems which must additionally house the oxidant within the cell [66]. These batteries are already commercially available and range in size from small button cells for hearing aids to very large batteries for electrical vehicle propulsion.

Zinc-air batteries have some properties of fuel cells as well as batteries thus making it a contender to power electric vehicles. Another advantage of the zinc-air system is that it is relatively safe as it does not require volatile material and is thus not prone to catching fire, , and it has a long shelf life, indefinite in fact, if stored in a dry state but are best used within three years of manufacture [67].

However, this battery cannot be used in a sealed battery holder as air must be come in. Some other disadvantages of the zinc-air battery is that zinc corrosion can produce hydrogen which could build-up in enclosed areas, short-circuiting the cell and deep discharge below 0.5V/cell may result in electrode leakage.

- **Li-S Batteries**

Li-S batteries due to their light weight (practical energy densities > 600Wh/kg, 2.5 – 1.7 V) and the safe, abundant low cost cathode material constitute a promising technology for future mobile applications. Its outstanding potential has e.g. been demonstrated as the night time power source on the longest solar-powered airplane flight in 2008. The Li-S battery consists of a Li metal anode, an organic liquid electrolyte and a cathode made of a composite of sulphur and mesoporous carbon. During discharge, lithium dissolves from the anode and reacts with sulphur of the anode to form Lithium polysulphides, $S_8 \rightarrow Li_2S_8 \rightarrow Li_2S_6 \rightarrow Li_2S_4 \rightarrow Li_2S_3$, and finally to Lithium sulphide, while on charging, Li_2S as well as the polysulphides are reduced again and Li is plated on the anode. Despite its inherent advantages, Li-S battery technology requires further progress in the coming decades to overcome challenges in terms of cycle life, cycle efficiency, self-discharging etc. mostly related to the solubility of Li polysulphides in the available electrolytes. The problems can be mitigated by electrolyte additives, Li anodes protected by solid electrolyte separators and coating of cathodes by hydrophilic layers. Another approach is to keep the sulphur accessible to electrons and lithium by immobilizing it in carbon nanostructures.

- **Sodium-Based Batteries**

In the sodium-sulphur (NaS) battery (2.08V, ~120Wh/kg) Na^+ ions from a molten sodium metal anode pass at 300-350°C through the ceramic Na^+ ion electrolyte β-alumina and react with the molten sulphur of the cathode to form sodium (poly) sulphides. As sulphur is an insulator, it is combined with a porous carbon-sponge matrix has to be used to ensure electronic conductivity. The high temperature, corrosive nature of Na, and the potential for catastrophic failure limit applications to large-scale stationary systems. NaS battery technology was demonstrated at over 200 sites (By NGK Insulators, Ltd. / Japan) with installations up to 245 MWh (34 MW) unit e.g. for the stabilization of the power output from wind parks. See Figure 33 on the schematic representation of NaS battery.

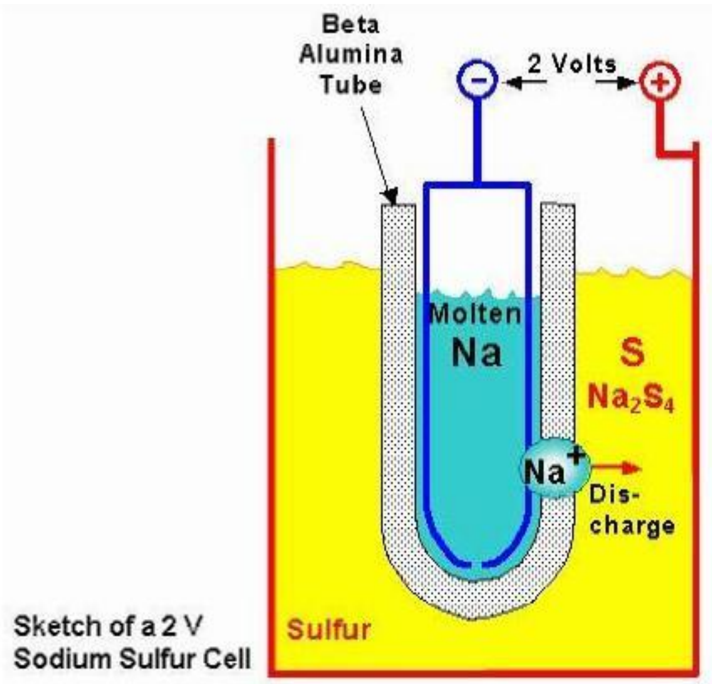

Figure 33 Schematic representation of NaS battery

Research for a safe alternative with a long cycle life sparked the development of the $NaNiCl_2$ or ZEBRA (invented by the Zeolite Battery Research Africa Project (ZEBRA) at Council for Scientific and Industrial Research (CSIR) labs / South Africa) battery (2.58V, 90W/kg, ~140W/kg) and similar Na-metal halide batteries. The Na-$NiCl_2$ battery has been tested in various electric vehicles (Think, Daimler), a significant drawback is however that the battery has to be stored in molten charged state. Once the $NaAlCl_4$ solidifies (below 157°C in the discharged state), a non-destructive restart takes several days. See Figure 34 [68].

Figure 34 ZEBRA battery

6. Project Description

TS (Tozzi Storage) plant is used to store and distribute electrical energy from non-programmable renewable sources.

The preexisting production plant is constituted by the following RES:

- A 17,25 kW photovoltaic plant carried out with solar panels (Trina Solar TSM-PC05-230 Wp).
- A 6.7 kWp wind turbine (Tozzi Nord TN420, connected to the grid through an AFE back to back converter).

In this case the load is composed by all the electrical utilities of a cheese factory.

Based on this pre-existing system configuration an ESS named TS (Tozzi Storage) has been installed and it is composed by two subsystem: PCS (Power Control system) and BESS (Battery Energy Storage System).

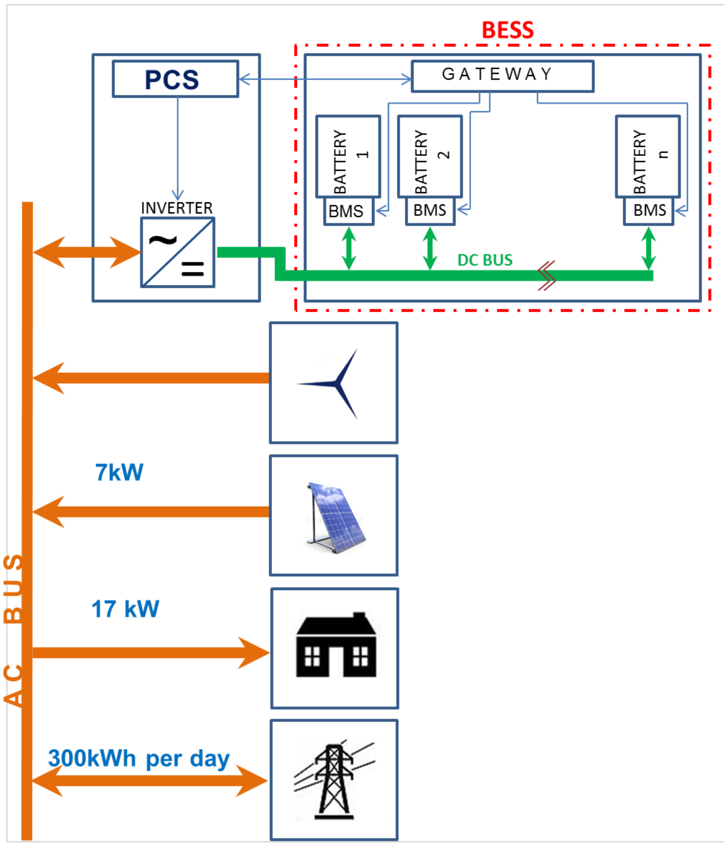

Figure 35 Microgrid configuration

The system allows to manage efficiently the energy flow from renewable sources to the load, according to demand. The produced energy can be injected into the grid, supplied to the load directly or stored in batteries.

7. Plant Analysis

7.1 Test Plant Location

The site chosen for the construction of the test plant has been the cheese factory named “Il Buon Pastore” located in Sant’Alberto in the province of Ravenna: one main reason has been the presence of a WT and a PV plant which supply energy to the cheese factory.

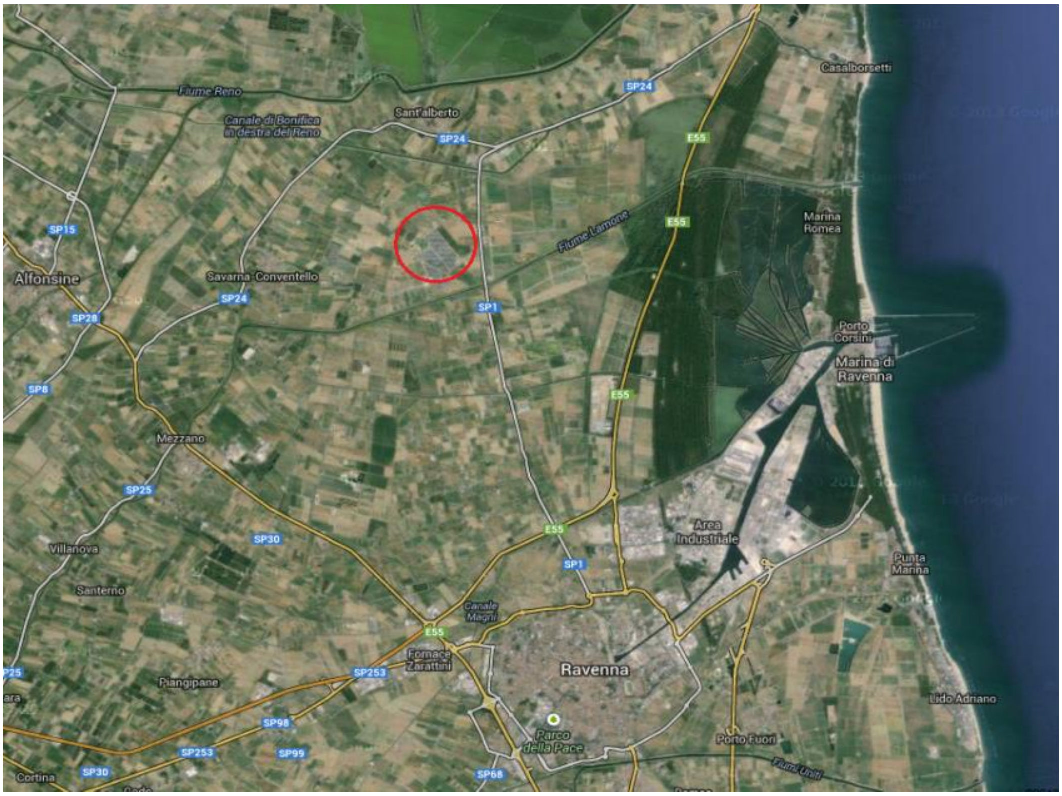

Figure 36 Test plant location, Forello street, Sant'Alberto (RA)

The choice of this site is also motivated by a real problem: due to structural failure of the network, the farm suffers frequent black outs that impede the normal operation of production activities and storage of goods.

Figure 37 Wind turbine.

Figure 38 PV plant on the roof of the cheese factory.

The position of the TS according to the project has been strategically chosen, next to the WT in order to be as close as possible to all system components.

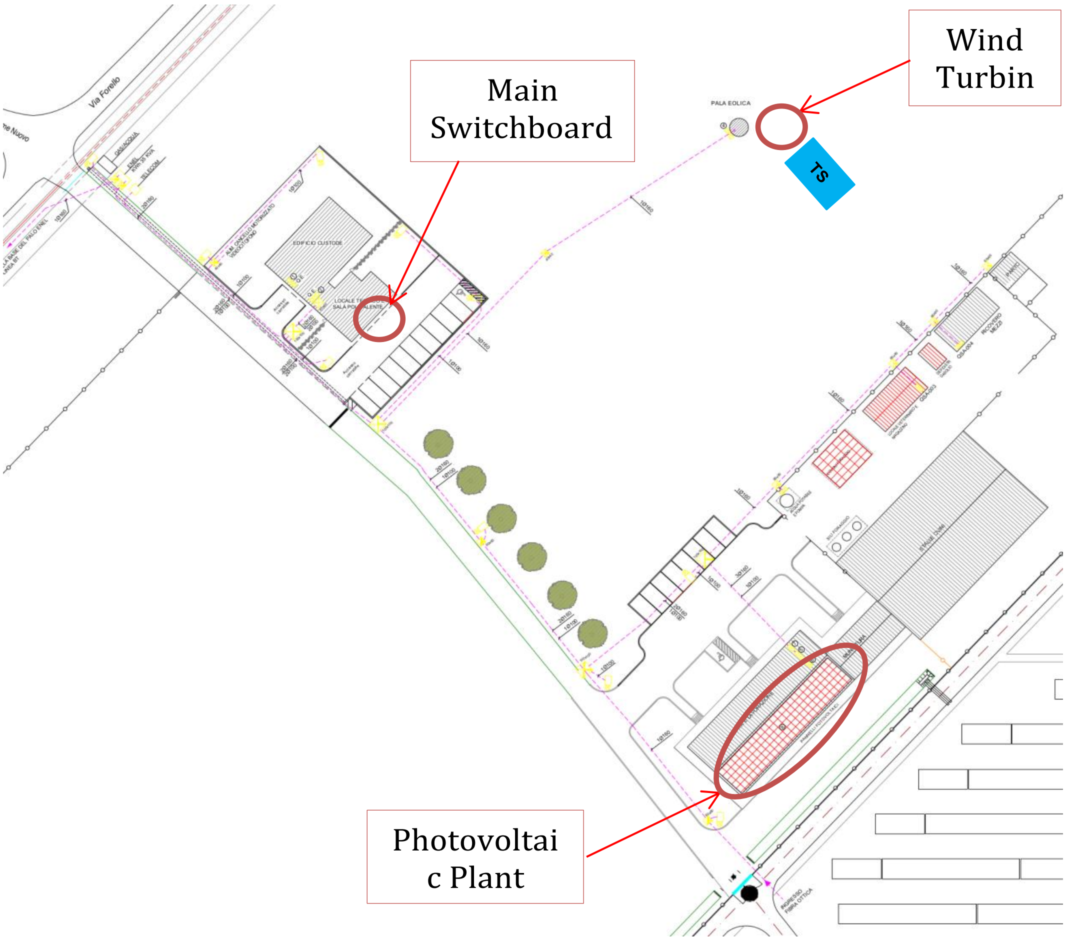

Figure 39 Planimetry of the site of TS installation

7.2 Study of the energy production from the PV plant

7.2.1 Description of the PV plant

The PV plant is three-phase current and connected in parallel to the public grid, supplying the produced electricity to the grid in the condition of net metering (TISP).

The energy flow depends on the electrical consumer and the power produced by the PV plant. In the period of absence of energy production (during the night), the public grid supplies the necessary energy to satisfy the load demand. The working system is defined as “grid connected”.

The PV generator, defined as the ensemble of panels and the related accessories, has a total power of 17,250 kWp and it is composed by 75 modules, each has the power of 230 Wp.

The plant consists of:

- PV Generator
- Conversion Group and measurement and data acquisition
- Electricity meter (property of ENEL)

The singles PV modules are made up 60 cells of multicrystalline silicon:

- Model: Trina solar TSM-230PC05
- Output Power: 230 Wp
- Maximum Voltage: 29,8V
- Maximum Current: 7,66A
- Open Circuit Voltage: 37,0V
- Current short circuit: 8.20A
- Efficiency: 14,1 %

The reported values are measured in standard conditions: irradiation $1000W/m^2$, cell temperature 25°C.

The modules are connected in series to form 4 strings; n.3 of these are composed by 19 modules and n.1 by 18 modules, wired individually to the inverter. The string sizing has been carried out taking into account the continuous voltage limit of the converter DC/AC. Blocking diode and protection have been installed in the field switchboard for overvoltages.

The inverter was sized for a nominal power of 30 kW, with the following characteristics:

- Model: SMA-ITALIA Sunny Tripower STP 17000TL-10
- Power DC max: (with cosΦ=1) 17410W
- Voltage DC max: 1000V

- Voltage range MPP: 400/800V
- Nominal power in AC: 17000W
- Nominal grid voltage 3/N/PE,: 230/400V
- Voltage range in AC 160/280V
- Nominal current in AC: 24,6A
- Maximum short circuit current: 0,05kA
- Grid nominal frequency: 50Hz
- Working range at grid frequency. 44/55Hz

The converter and controller group of the power is appropriate for the power transfer from the PV plant to the distribution grid, according the technical norm requirements and safety norms. The current and voltage values in the input of these devices are compatibles with those of the respective PV plant, while the current and voltage values in the output are compatibles with those of the grid where the system is connected.

The conditioning group of the power is mainly composed by:

- Incoming section from the PV plant (DC)
- Modular inverter with forced commutation and microprocessor which consist of command logic, protections, auto diagnosis and measurements.

The conversion group possesses a system able to read instantaneously the significant working parameters (i.e. produced energy, power, working time, etc…) as an instantaneous or historical data. Moreover, the system is equipped with an interface for connecting the PC in order to download the working data.

The inverter works optimizing the maximum power of the solar generator (MPPT). When the supplied energy is not enough to supply current to the grid, the inverter interrupt automatically the connection and it is stopped.

In the conversion device, according to the connection rule to the LV distribution grid prescribed by ENEL specification, are included the following devices:

- N1. Energy and power meter

- N1. Interface panel corresponding to the resolution 84/12 and attachment A70, with the function of: protection of minimum and maximum voltage and frequency.
- N1. Three pole circuit breaker as a general device for the plant switch.

The PV generator is located on the roof of the building where the cheese is produced; in particular the roof give the supporting surface to the modules in order to have the same angle (about 10°).

7.2.2 Analysis of the PV Plant Production

The power and energy data have been acquired for a year through a grid analyser. These data are necessary in order to size the ESS plant to absorb the peak power and the total energy produced.

Next table and figure show the energy data produced for a year, July 20012 – July 2013.

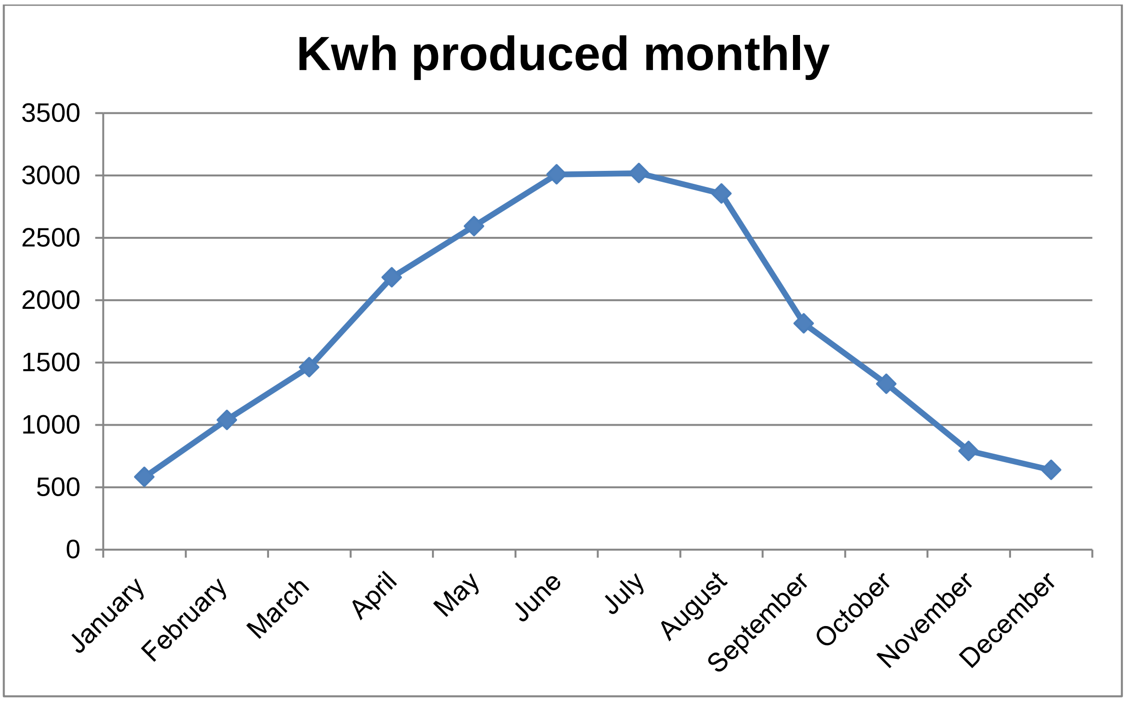

Figure 40 Energy produced monthly from the PV plant.

	Energy produced monthly, kWh											
Day	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	37	9	64	71	83	101	102	105	58	71	43	21
2	4	7	61	28	29	82	103	101	73	67	58	12
3	34	46	75	70	103	64	109	101	26	67	38	48
4	33	59	77	65	84	93	107	102	43	70	15	6
5	37	28	34	15	43	105	102	102	57	61	34	26
6	24	38	8	86	50	105	60	80	81	69	50	42
7	24	30	23	65	50	111	109	103	88	62	57	16
8	7	63	29	70	66	110	114	99	91	34	52	0
9	6	41	50	55	106	70	112	100	89	20	50	24
10	13	48	60	58	48	89	110	98	85	49	27	38
11	4	5	47	93	80	116	111	101	77	34	16	45
12	9	23	65	70	114	115	106	99	67	16	1	41
13	4	19	45	101	116	111	93	92	27	26	11	9
14	9	41	18	102	119	117	110	90	60	29	23	5
15	34	59	37	104	108	109	112	94	60	14	47	6
16	7	65	80	97	43	109	111	97	81	70	19	17
17	14	51	51	93	62	109	110	94	82	50	16	5
18	9	50	29	101	111	106	109	95	84	41	8	7
19	15	66	88	102	72	105	107	96	33	20	3	31
20	5	14	49	27	103	110	109	93	77	54	13	27
21	13	7	92	28	91	111	64	96	88	48	42	7
22	16	4	92	85	108	110	65	88	82	34	25	11
23	30	3	57	81	78	113	68	86	39	57	30	8
24	6	74	12	103	75	96	52	90	59	60	29	9
25	41	66	9	105	61	101	103	91	73	55	9	4
26	50	76	16	63	110	55	102	38	35	10	39	4
27	49	11	64	52	123	105	51	101	10	13	5	5
28	7	38	18	72	88	55	99	99	33	15	4	40
29	17		31	69	102	113	99	93	17	40	20	44
30	11		14	49	115	114	106	84	40	54	7	41
31	12		66		53		102	45		19		39
Total (kWh)	**582**	**1039**	**1463**	**2182**	**2594**	**3008**	**3019**	**2855**	**1813**	**1329**	**792**	**639**
Daily average	**19**	**37**	**47**	**73**	**84**	**100**	**97**	**92**	**60**	**43**	**26**	**21**

Table 4 Data of the produced energy from the PV plant in the year 2012

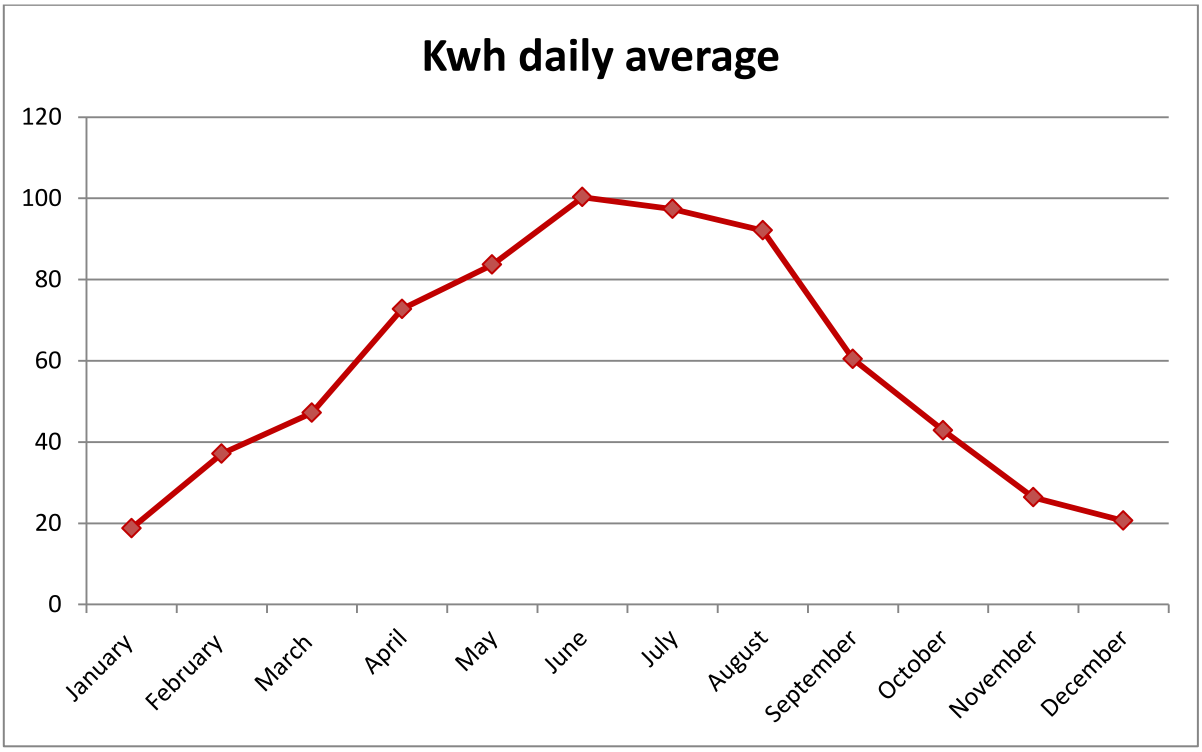

Figure 41 Daily average of the energy produced from the PV plant.

From these plots, the different production is noted between the winter months and the summer months. The maximum production was about 3 MWh in July, while the minimum was approximately 600 kWh in January.

The daily average of production is another data to take into account in order to choose the best ESS size. In this case an important variation has been noted between the winter months, 20 kWh and the summer months, 100 kWh.

In order to see the power peaks data have been acquired every 5 min in different days of the year.

Time	Power kW	Time	Power kW	Time	Power kW
00:00	0,0	08:00	1,7	16:00	3,4
00:05	0,0	08:05	2,1	16:05	7,0
00:10	0,0	08:10	4,7	16:10	5,8
00:15	0,0	08:15	6,3	16:15	7,4
00:20	0,0	08:20	7,5	16:20	7,2
00:25	0,0	08:25	6,2	16:25	6,8
00:30	0,0	08:30	8,8	16:30	6,6
00:35	0,0	08:35	6,7	16:35	6,2
00:40	0,0	08:40	7,7	16:40	5,9

00:45	0,0	08:45	9,1	16:45	5,3
00:50	0,0	08:50	9,2	16:50	5,2
00:55	0,0	08:55	8,9	16:55	4,9
01:00	0,0	09:00	6,8	17:00	4,7
01:05	0,0	09:05	8,9	17:05	4,3
01:10	0,0	09:10	10,2	17:10	3,9
01:15	0,0	09:15	10,8	17:15	3,7
01:20	0,0	09:20	8,8	17:20	3,2
01:25	0,0	09:25	7,8	17:25	3,0
01:30	0,0	09:30	6,8	17:30	2,6
01:35	0,0	09:35	9,1	17:35	2,2
01:40	0,0	09:40	6,3	17:40	2,0
01:45	0,0	09:45	5,5	17:45	1,8
01:50	0,0	09:50	7,2	17:50	1,5
01:55	0,0	09:55	11,8	17:55	1,4
02:00	0,0	10:00	6,0	18:00	1,3
02:05	0,0	10:05	7,8	18:05	1,3
02:10	0,0	10:10	4,0	18:10	1,1
02:15	0,0	10:15	4,4	18:15	1,1
02:20	0,0	10:20	3,7	18:20	1,1
02:25	0,0	10:25	10,5	18:25	1,1
02:30	0,0	10:30	8,4	18:30	1,0
02:35	0,0	10:35	9,5	18:35	1,0
02:40	0,0	10:40	13,4	18:40	1,0
02:45	0,0	10:45	9,5	18:45	0,9
02:50	0,0	10:50	11,9	18:50	0,9
02:55	0,0	10:55	6,6	18:55	0,8
03:00	0,0	11:00	13,4	19:00	0,7
03:05	0,0	11:05	11,8	19:05	0,6
03:10	0,0	11:10	14,6	19:10	0,5
03:15	0,0	11:15	13,5	19:15	0,4
03:20	0,0	11:20	13,8	19:20	0,3
03:25	0,0	11:25	14,4	19:25	0,2
03:30	0,0	11:30	10,4	19:30	0,1
03:35	0,0	11:35	10,4	19:35	0,1
03:40	0,0	11:40	8,8	19:40	0,0
03:45	0,0	11:45	8,5	19:45	0,0
03:50	0,0	11:50	6,0	19:50	0,0
03:55	0,0	11:55	6,3	19:55	0,0
04:00	0,0	12:00	8,8	20:00	0,0
04:05	0,0	12:05	8,6	20:05	0,0
04:10	0,0	12:10	4,6	20:10	0,0
04:15	0,0	12:15	5,7	20:15	0,0
04:20	0,0	12:20	6,7	20:20	0,0
04:25	0,0	12:25	4,0	20:25	0,0

04:30	0,0	12:30	9,8	20:30	0,0
04:35	0,0	12:35	15,0	20:35	0,0
04:40	0,0	12:40	13,0	20:40	0,0
04:45	0,0	12:45	14,5	20:45	0,0
04:50	0,0	12:50	13,7	20:50	0,0
04:55	0,0	12:55	13,5	20:55	0,0
05:00	0,0	13:00	12,6	21:00	0,0
05:05	0,0	13:05	11,4	21:05	0,0
05:10	0,0	13:10	10,6	21:10	0,0
05:15	0,0	13:15	13,4	21:15	0,0
05:20	0,0	13:20	12,7	21:20	0,0
05:25	0,0	13:25	12,6	21:25	0,0
05:30	0,0	13:30	12,0	21:30	0,0
05:35	0,0	13:35	12,0	21:35	0,0
05:40	0,0	13:40	12,2	21:40	0,0
05:45	0,0	13:45	12,6	21:45	0,0
05:50	0,0	13:50	12,3	21:50	0,0
05:55	0,0	13:55	12,4	21:55	0,0
06:00	0,0	14:00	11,7	22:00	0,0
06:05	0,0	14:05	13,2	22:05	0,0
06:10	0,0	14:10	12,5	22:10	0,0
06:15	0,0	14:15	12,0	22:15	0,0
06:20	0,0	14:20	11,0	22:20	0,0
06:25	0,0	14:25	11,8	22:25	0,0
06:30	0,0	14:30	10,8	22:30	0,0
06:35	0,0	14:35	11,7	22:35	0,0
06:40	0,0	14:40	10,5	22:40	0,0
06:45	0,0	14:45	10,2	22:45	0,0
06:50	0,0	14:50	8,7	22:50	0,0
06:55	0,0	14:55	4,4	22:55	0,0
07:00	0,0	15:00	3,7	23:00	0,0
07:05	0,2	15:05	7,1	23:05	0,0
07:10	1,0	15:10	9,1	23:10	0,0
07:15	1,1	15:15	9,7	23:15	0,0
07:20	0,4	15:20	7,6	23:20	0,0
07:25	0,5	15:25	10,8	23:25	0,0
07:30	0,5	15:30	7,5	23:30	0,0
07:35	0,7	15:35	9,2	23:35	0,0
07:40	0,9	15:40	10,0	23:40	0,0
07:45	1,0	15:45	10,0	23:45	0,0
07:50	1,2	15:50	9,6	23:50	0,0
07:55	1,4	15:55	9,4	23:55	0,0

Table 5 Daily average power of the PV plant on 06/04/2012

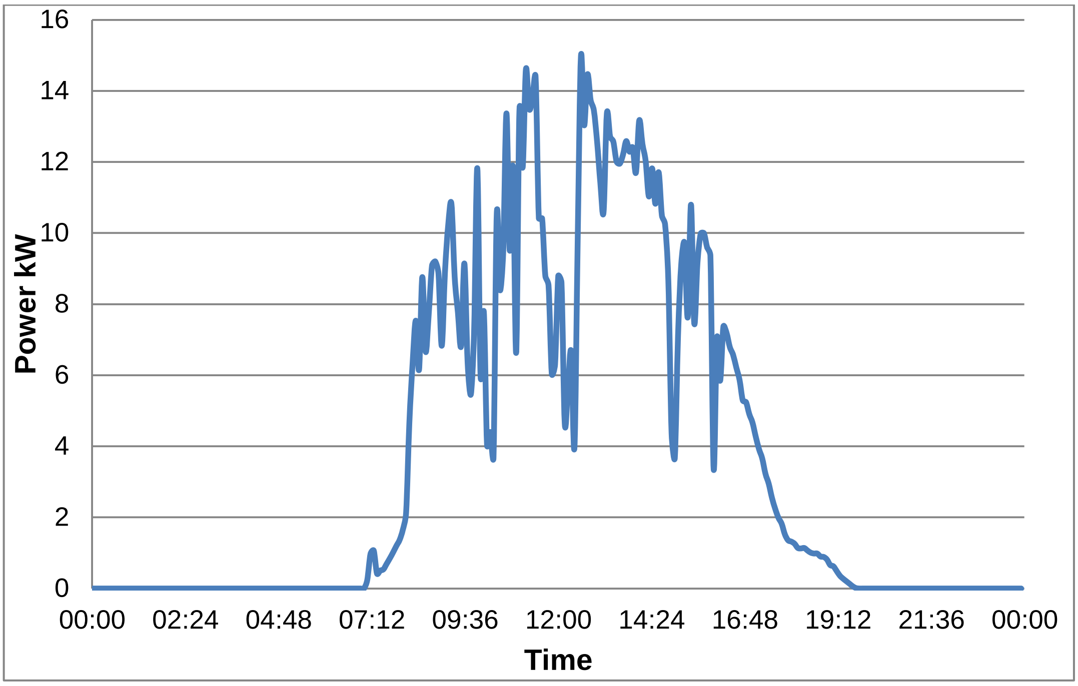

Figure 42 Daily average power of the PV plant on 06/04/2012

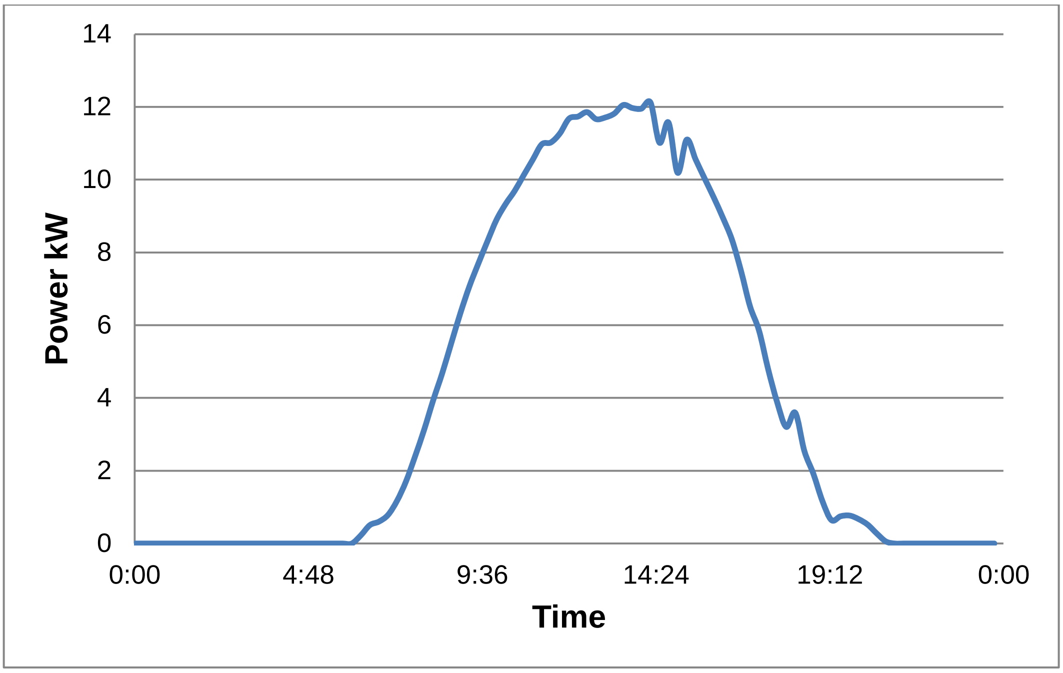

Figure 43 Daily average power of the PV plant on 04/07/2012

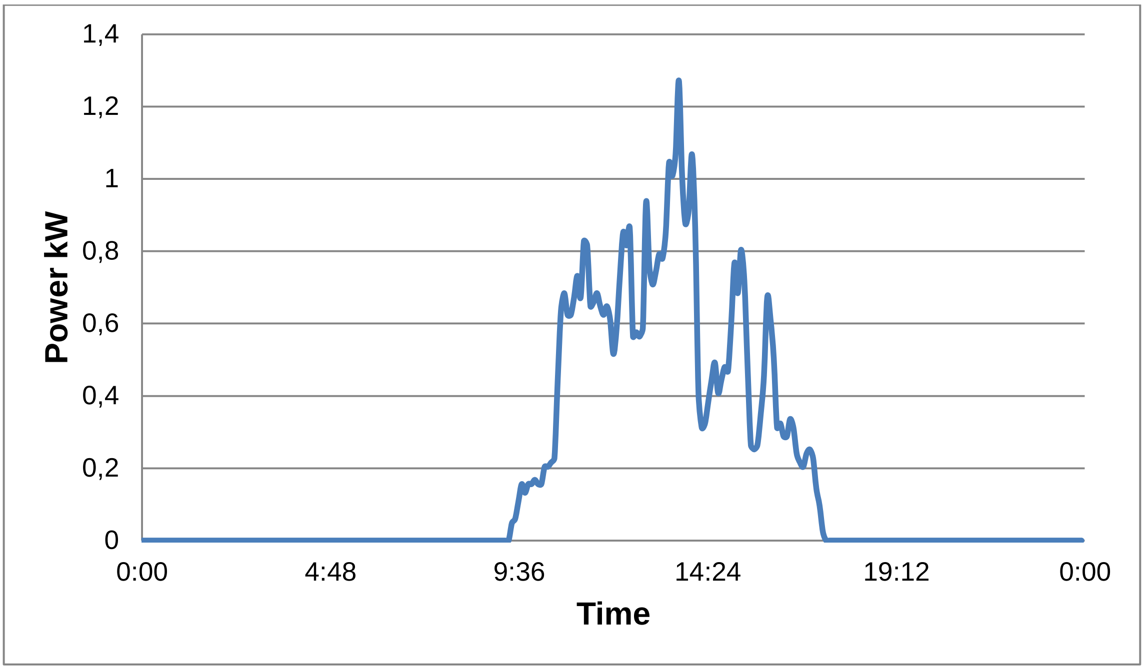

Figure 44 Daily average power of the PV plant on 12/12/2012

7.3 Study of the energy production from the wind farm

7.3.1 Description of the wind farm

The small wind turbine is an horizontal axis type, in which the tower carries the nacelle to the top. The nacelle consists of a low and high speed shaft, gearbox, electrical generator and the auxiliary devices. The rotor is assembled in the slow shaft end, it is composed by a steel hub with the blades. The nacelle is able to rotate in order to maintain always the axis of the machine parallel to the direction of the wind (yaw orientation). The produced energy is carried to the conversion group located within an electrical cabin located close to the tower though electrical cables.

The generator is an asynchronous type with permanent magnets.

The energy deployment into the national grid is carried out through a frequency AC/DC/AC converter, which presents an intermediate DC circuit in order to separate the voltage and frequency values; with deployment into the grid according to the nominal values of the electric grid.

The wind turbine is equipped with a drum brake to stop turbine in emergency situation such as extreme gust events or over speed.

In case of over speed and consequently mechanical danger for the blades, the turbine has a system, which is able to move the blades in order to put on safety position; obviously the machine is stopped.

All functions are monitored and controlled by a control unit based on microprocessors . The shell of the nacelle protects all components from rain, snow, dust, sun, etc…

The nacelle consist of the following assembled subsystems:

- N.3 blades of steel/GRP with a connector hub/blade.
- Connecting hub between the electrical generator and the three-blades rotor.
- Multipolar electric generator with permanents magnets , consisting of two rotor system.
- Shaft for the transmission of the aerodynamic torque from the wind rotor to the electric generator.
- Vane.
- Hardware and software control of the system.
- Electrical and signal cables from the nacelle to the tower base

The wind power system is connected in parallel to the public grid, deploying part of the energy produced.

The energy flow depends on the electrical consumer and the power of the WT. In the period of absence of energy production, the public grid supplies the necessary energy to satisfy the load demand. The working system is defined as “grid connected”.

The WT has a total power of 6.5 kWp and is supplied by Tozzi Nord S.r.l.

The plant consists of:

- Wind turbine
- Conversion Group and measurement and data acquisition
- Electricity meter (property of ENEL)

The converter and power controller are appropriate for the power transfer from the wind farm to the distribution grid, according the technical norm requirements and safety norms. The current and voltage values in the input of these devices are compatible with those of the respective WT plant, while the current and voltage values in the output are compatible with those of the grid to which the system is connected.

The power conditioning group is mainly composed by:

- Incoming section from the wind farm (AC)
- Modular inverter with forced commutation and microprocessor which consist of command logic, protections, auto diagnosis and measurements.

The conversion group possesses a system able to read instantaneously the significant working parameters (i.e. produced energy, power, working time, etc…) as an instantaneous or historical data. Moreover, the system is equipped with an interface for connecting the PC in order to download the working data.

The inverter works optimizing the maximum power of the WT. When the supplied energy is not enough to supply current to the grid, the inverter interrupts automatically the connection.

7.3.2 Analysis of the wind farm production

The power and energy data have been acquired for a year through a grid analyser. These data are necessary in order to size the ESS plant to absorb the peak power and the total energy produced.

Next figure shows the daily power of the wind farm on 04/04/2012.

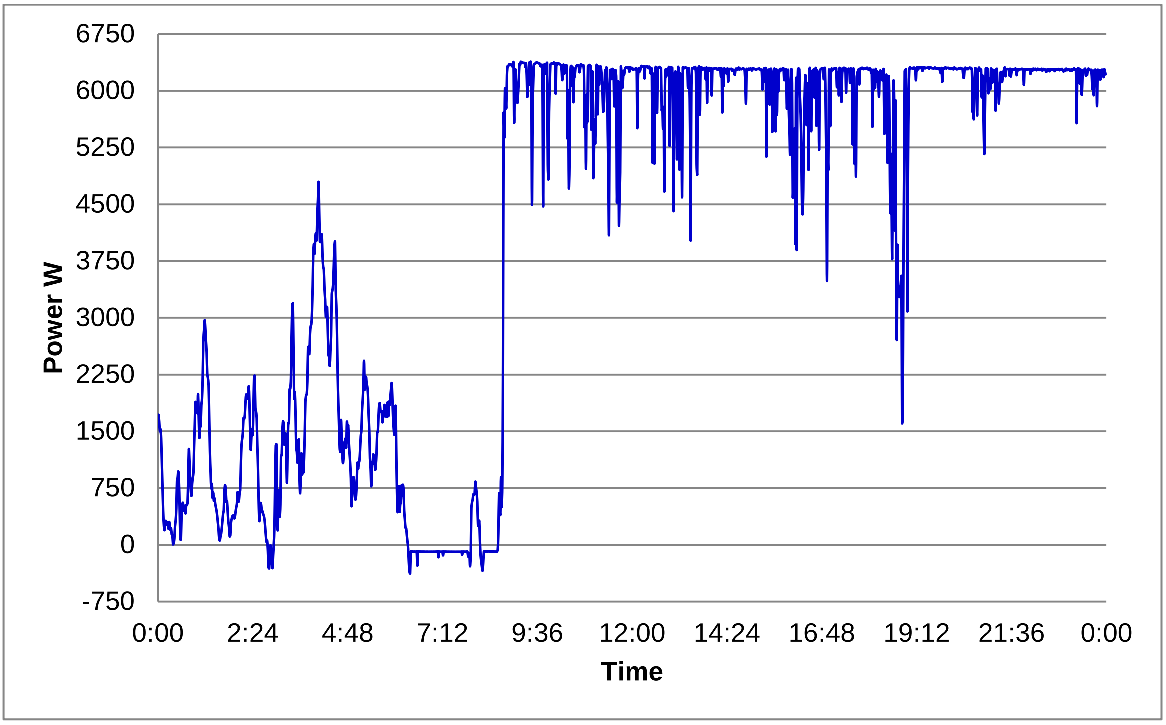

Figure 45 Daily power of the Wind farm on 04/04/2012

The energy produced on this day was about 100 kWh.

The average energy of the turbine measured daily in the period of one year was 70 kWh.

7.4 Load Analysis

The cheese factory “Il Buon Pastore” has been chosen as the place to install the TS. This cheese factory meets all requirements to test all system applications.

In the cheese factory area there is a zone dedicated to the management and flock care with premises destined to the milking and milk works and premises to age the dairy products. The cheese factory area is around 71 ha, and possesses two cheese factory yards with a capacity of 500 heads.

The loads present in the cheese factory are listed below:

Load Type	Monophase	Triphase	Power (kW)
Refrigeration Unit 1		X	11,00
Refrigeration Unit 2		X	5,00
Cashier Counter	X		1,00
Air Conditioning - Shop	X		1,00
Air Conditioning - Butcher	X		0,30
Air Conditioning – Dairy Work Room	X		0,30
Air treatment room 1		X	2,00
Air treatment room 2		X	2,00
Washer unit		X	9,00
Hydro-wash Machine		X	1,50
Ice Storage		X	2,60
Refrigerator	X		0,40
Multi-use Tub		X	0,70
Transfer Pump for milk		X	1,00
Compressor		X	1,47
Vacuum Pump		X	4,00
Pump for milk		X	1,00
Electronic System	X		0,30
Motor for Tub 1		X	1,10
Motor for Tub 2	X		0,40
Thermal Power Plant	X		1,00
Conveyor for Feeding 1		X	1,50

Conveyor for Feeding 1		X	1,50
Transporter		X	0,70
N.2 Extraction Tower(2x0,7)		X	1,40
N. 3 SILOS (3x1,1kW)		X	3,30
Irrigation Plant: N. 2 Electro Pump (2x2,2kW)		X	4,40
Electro Pump - Farmyard		X	2,20
Auxiliary Feed	X		0,20
Guardian House	X		3,00
N.46 Fluorescent Light 2x36W 230V – Ordinary Light	X		3,30
N.20 Fluorescent Light 2x36W 230V – Night/Emer. Light.	X		1,40
N.6 Incandescent Light 1x100W 110V	X		0,60
N.2 Projector 400W – Ext. Light	X		0,80
N.69 Incandescent Light 4x18W 230V –ORD. Light	X		5,00
N.23 Emergency Light 1x18W	X		0,40
N.9 Lights for Exterior Viability JM-E 150W	X		1,35
TOTAL			78,12

Table 6 Loads present in the cheese factory

A grid analyser has been installed to acquire data related to power and energy consumption in order to know the exact consumption of these loads.

In this way, data have been acquired for a period of 10 months with an interval of 10 s.

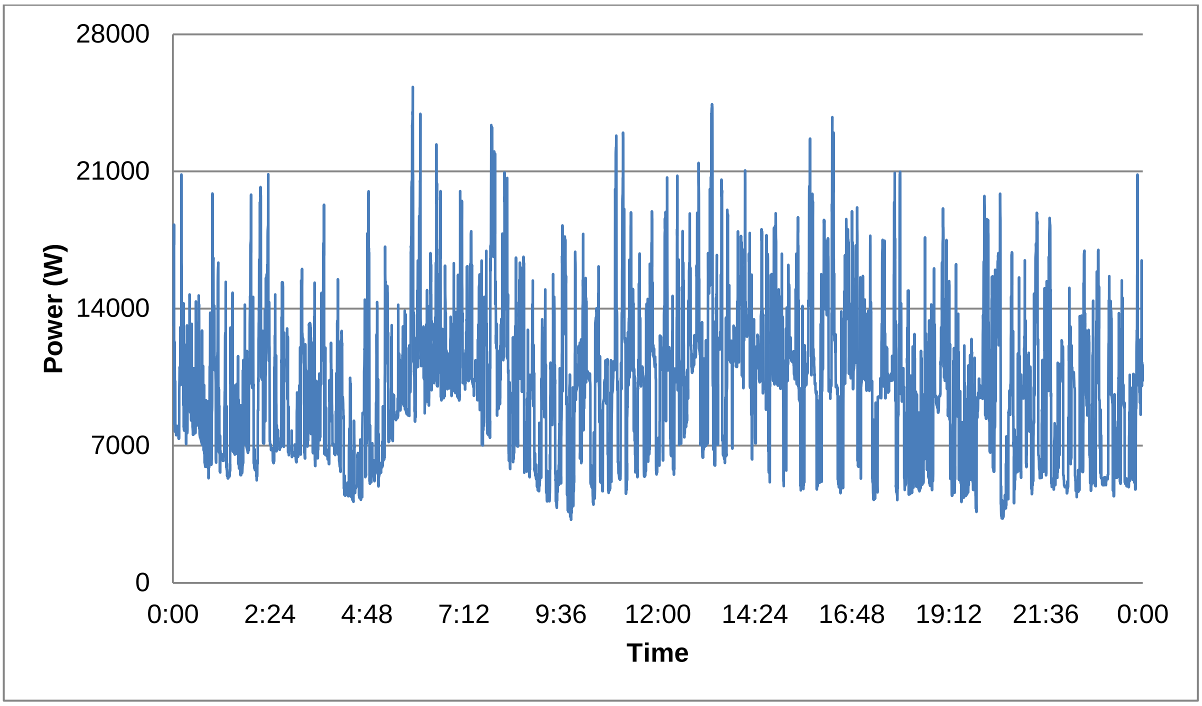

Figure 46 Variation of the power demand on 27/07/2012.

According to the measured data of energy consumption, it has been obtained a daily average of 300 kWh.

Next table shows the purchase of the total and monthly average energy after the exchange.

	Acquired Energy kWh		
PERIOD	**30/09/12**	**31/07/13**	**10 MESI**
F1	12929	20520	7591
F2	7562	11764	4202
F3	38000	45526	7526
TOTAL	58491	77810	19319
MONTHLY AVERAGE			1931,9
DAILY AVERAGE			64,4

Table 7 Purchased energy in a period of 10 months. Data of the Enel invoice.

Due to the cheese factory works change frequently depending on the season, the different consumption between the months of the year has to be into account.

In the following table the frecuent use of the main loads during a year and a day is showed.

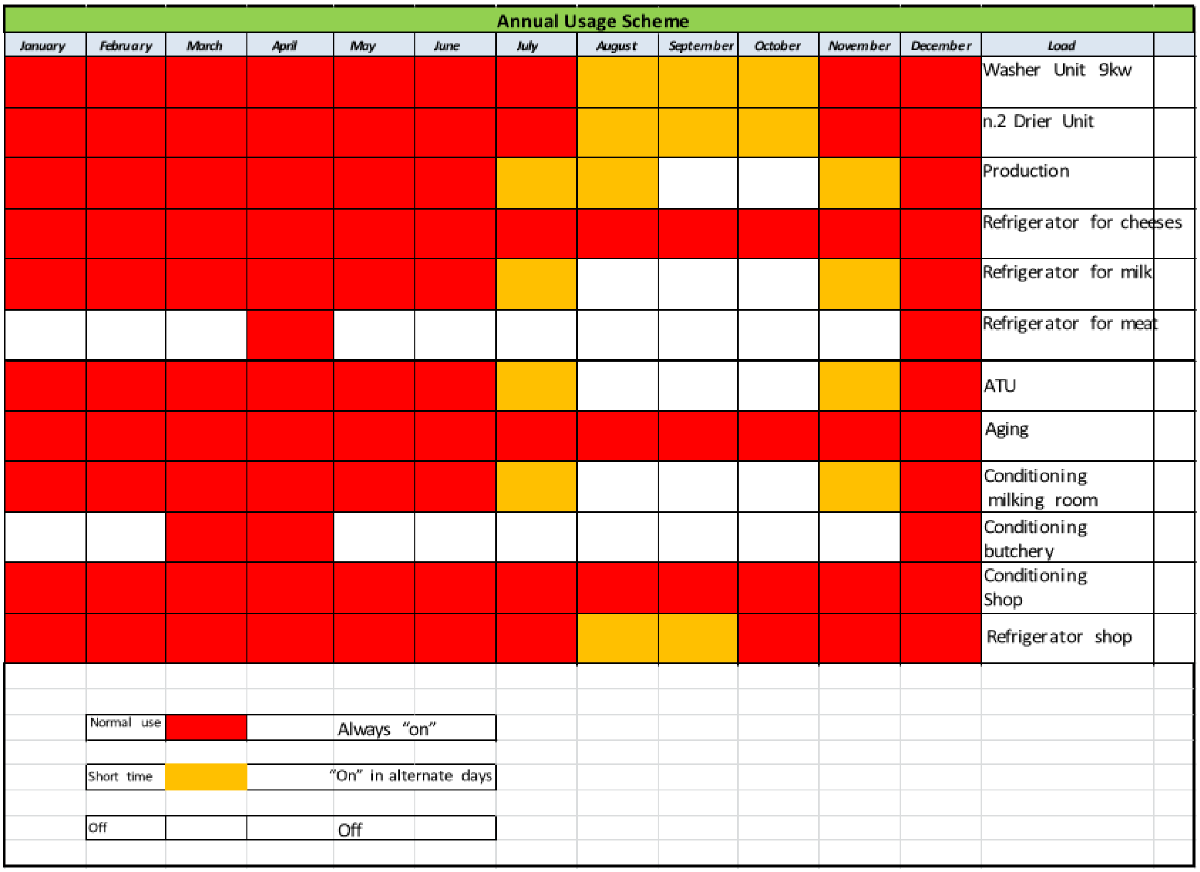

Table 8 Annual usage scheme of the cheese factory loads

Daily usage scheme of the loads			
Consumption	**Activity**	**from**	**to**
Minimun	Refrigerator Room conditioning Night-light Monitoring PC Illumination	19:30	05:30
Medium	Shop refrigerators Cheese factory activity non-productive Wash machine Milking Room conditioning Monitoring PC	13:00	19:30

Maximum	Production Sale Wash machine REfrigerator Room conditioning Monitoring PC	07:00	13:00
Low	Room conditioning Monitoring PC Milking Refrigerator Illumination	05:30	07:00

Table 9 Daily usage scheme of the cheese factory loads

Next table shows the data of the energy purchase for the cheese factory in three different months. Data provided by Enel.

	PERIOD				Consumption (kWh)
	DA	A			
	31/01/2012	29/02/12		N. MONTH	
F1	16195	17044,00	849,00		
F2	9583	10082,00	499,00	1,00	Daily Average
F3	41621	42443,00	822,00		72,33
TOT			2170,00		
	29/02/2012	31/03/12			
F1	17044	17850,00	806,00		
F2	10082	10721,00	639,00	1,00	Daily Average
F3	42443	43505,00	1062,00		83,57
TOT			2507,00		
	31/05/2012	30/06/12			
F1	18443	19170,00	727,00		
F2	11001	11210,00	209,00	1,00	Daily Average
F3	44263	44582,00	319,00		41,83
TOT			1255,00		

Table 10 Purchased energy monthly

7.5 Bus AC Study

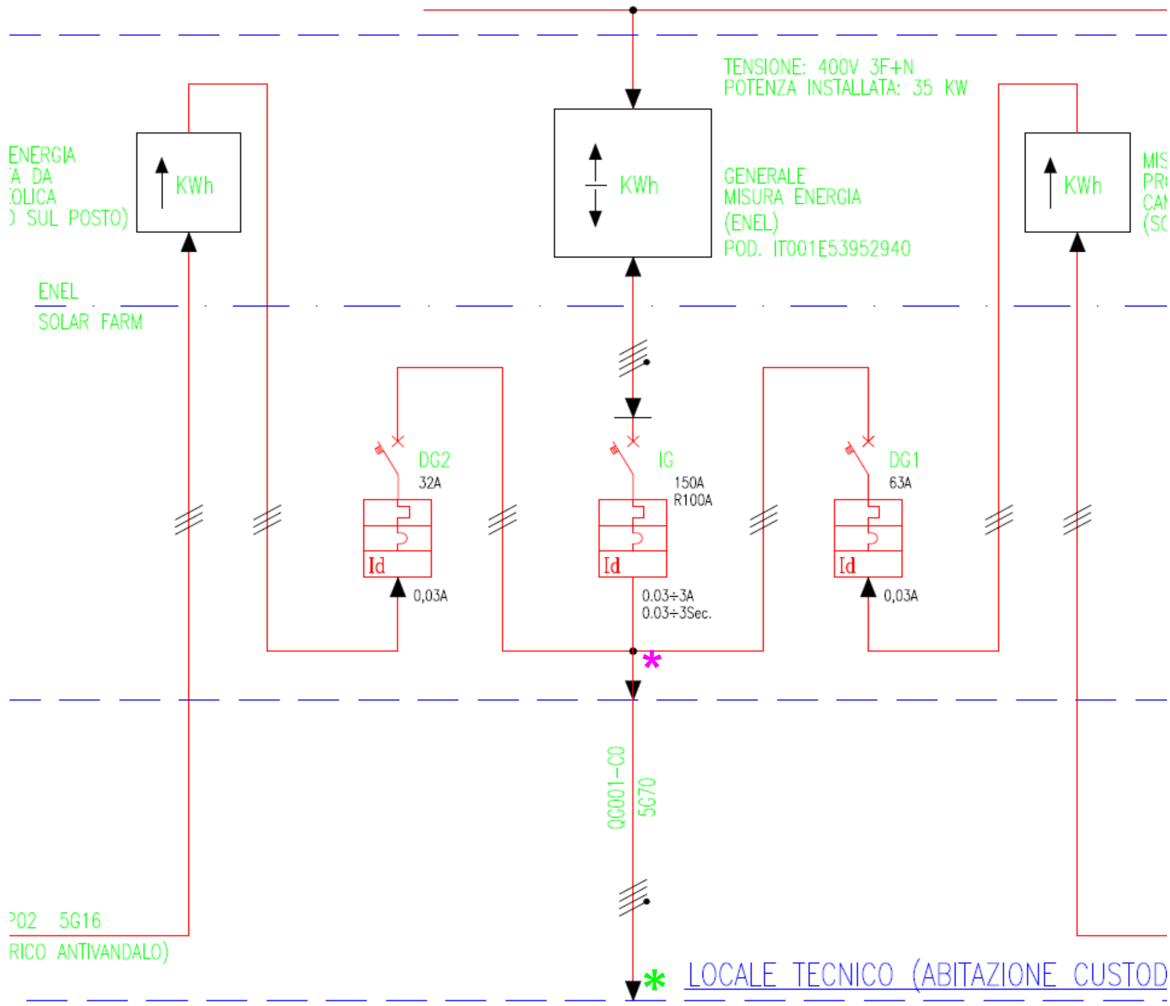

Figure 47 Scheme of the exchange configuration of the WT and the PV plant.

The bus AC is the line QG001-C0, where in the junction * the PV and WT production are collected and then going to the switchboard QG001. In this way, the self-production is encouraged, that is, the loads are firstly supplied by the energy produced Pv and WT. All production surpluses go to the public grid according to the agent (in this case Enel).

The fee of the energy deployment into the grid and produced by the PV plant is counted and paid by Enel, whereas the fee generated from the WT is not paid. The design is based on the choice of connecting the power cable to the batteries in the point * in order to reduce the length.

8. System Architecture

The system is composed by two RES, (a 7 kW WT and a 17 kW PV plant) loads present in the cheese factory and an energy storage system TS. All of these are connected to the grid through an AC Bus. The TMPC Tozzi Master Power Control is connected directly to the TS in order to control and supervise the entire system. Different grid analyser TGA are distributed on the system to monitor the energy flows.

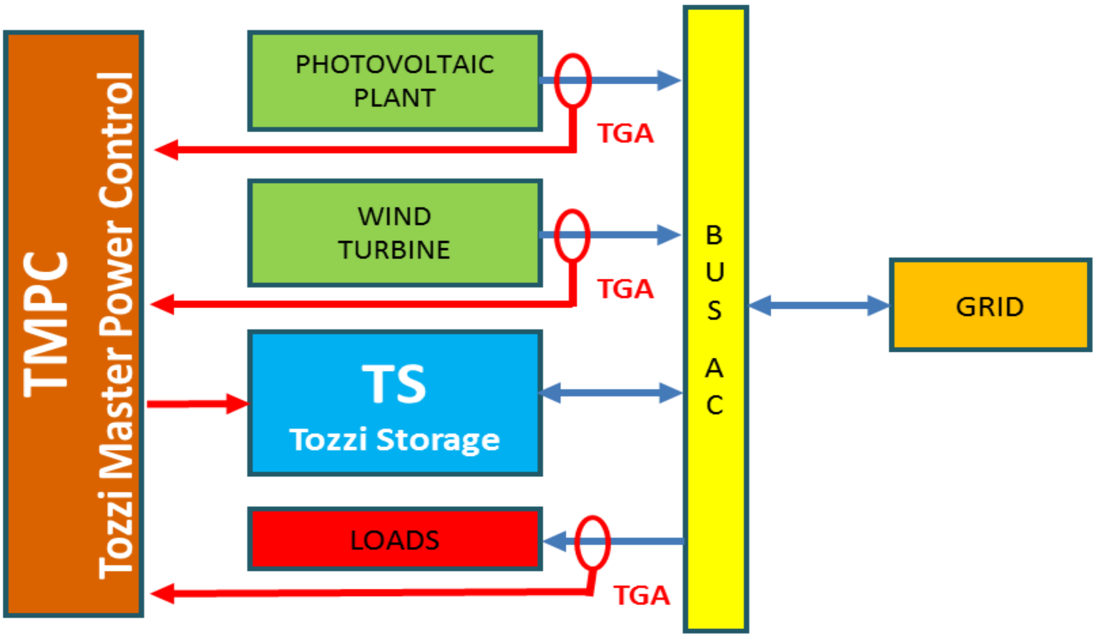

Figure 48 Scheme of the system.

8.1 Hardware Architecture

The main components of the hardware architecture are the Tozzi Storage (TS), Tozzi Master Power Control (TMPC) and the Tozzi Grid Analyser (TGA).

The TS is subdivided in two parts, a Power Control System (PCS) and a Battery Energy Storage System (BESS). These system is installed within a 20" container.

- The PCS is connected to the DC bus and consists of an 50 kW inverter connected to a switchboard where is installed the controller (National Instrument hardware).
- The BESS consists of a battery pack organized in parallel configuration and connected through a Battery Management System (BMS) to the DC bus.

Also it is connected to the AC bus in order to exchange energy with the grid and the RES.

The TMPC consists of different electronic devices connected to the TS, WT, PV plant and AC bus. A computer is used for monitoring and managing the energy flows of the system from a remote position.

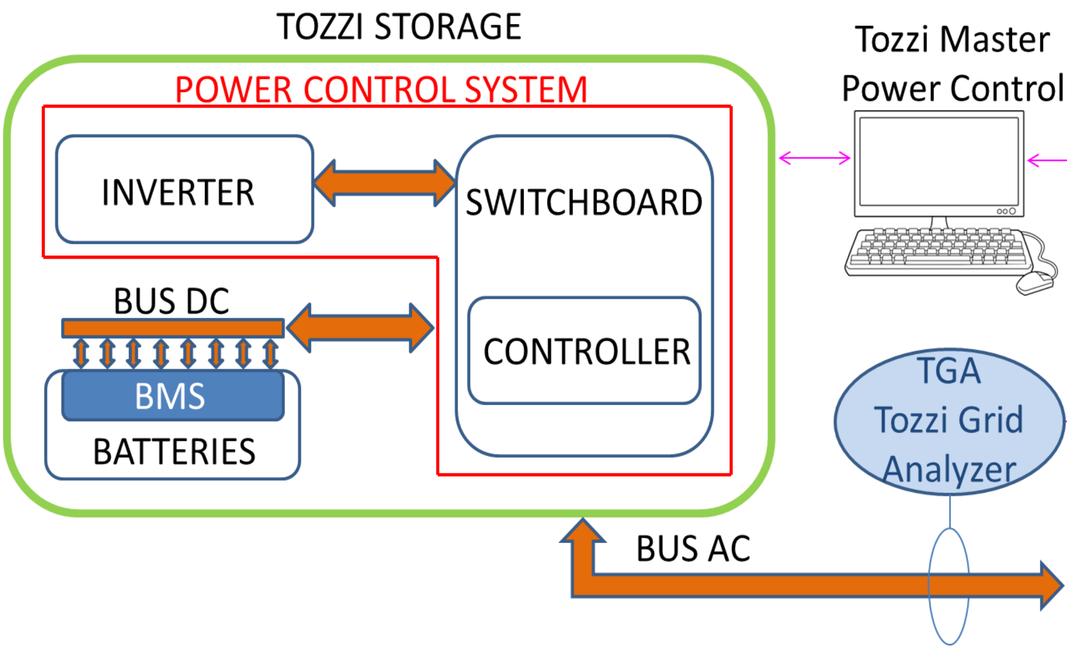

Figure 49 Hardware architecture.

8.2 Software Architecture

It is a distributed architecture where the controller is interfaced with the inverter and BMS. The different operations carried out within the PCS controller are realized for a FPGA and a microprocessor.

The software used for introducing the system logic into the National Instruments hardware (controller) is LabView.

The data acquisition is carried out for the TGA installed and transmitted to the TMPC.

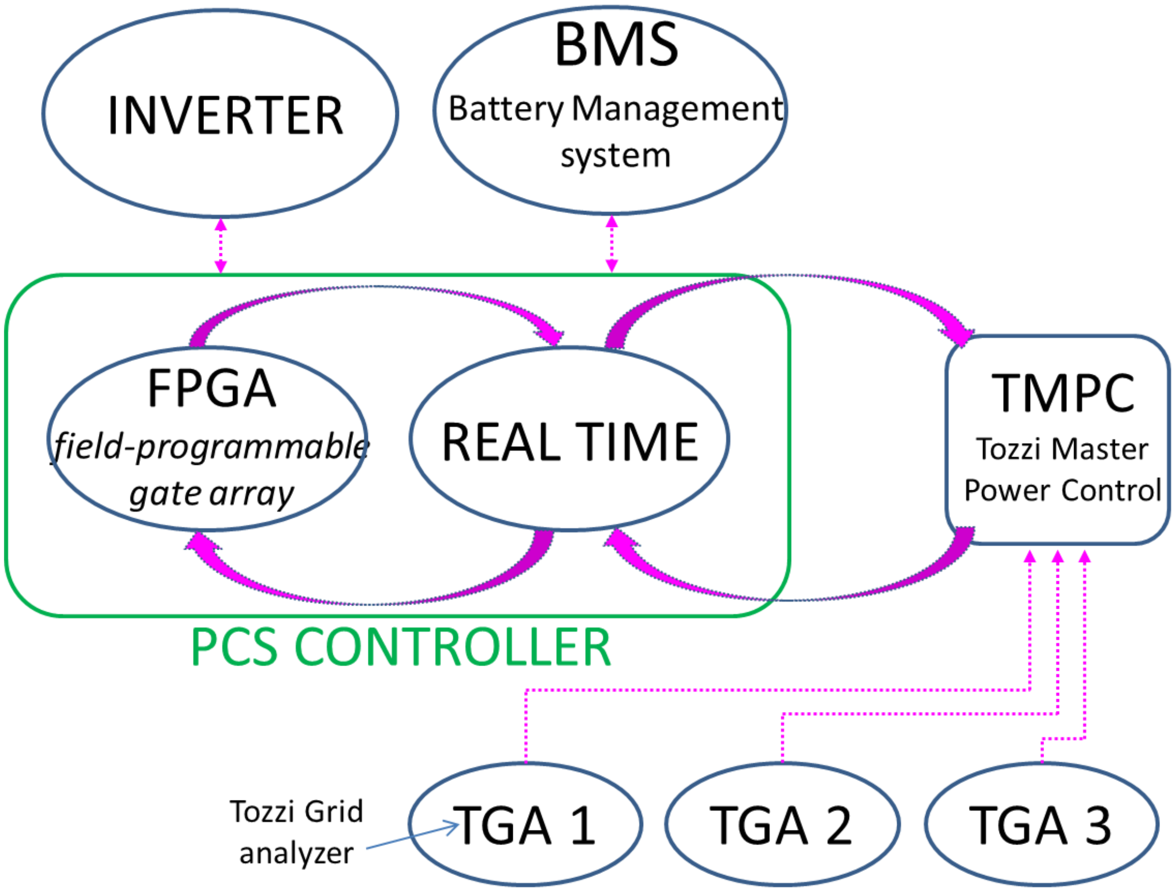

Figure 50 Software architecture.

8.3 Mechanical Architecture

The housing chosen for the ESS installation is a container ISO 20 feet modified in order to meet the system requirements.

The changes implemented are the following:

- Container with double door on both ends.
- N° 1 Door with window and air grill situated in the middle of the container. Dimension: 2000 x 1100 mm (height x width).
- N°7 Air grills. Dimension: 400 x 400 mm
- N°8 Roof fans, two of them without forced ventilation. One of these is connected to the ventilation system of the inverter. The roof fan situated near the switchboard is connected to the related ventilation connector.
- N°3 Grommet plates, model Murrplastik KDL/E 24/10 in the zone A (see Figure 51).
- N°4 Grommet plates REI 120, model Murrplastik KDL/E 24/10 in the zone C.
- Construction of a metallic channel painted like the colour of the interior container and situated in the upper part of the zone B, on the four sides and adjacent to each side.
- Construction of a metallic channel painted like the colour of the interior container and situated on the ground of the zone A.
- Interior lining REI 120 on the walls, doors and ceiling in the zone C. For the zone A and B has been applied a polyurethane lining with a thickness of 50 mm.
- Construction of a wall to separate zone C of zone B with a REI 120 lining.
- Construction of a shelving to collocate 8 batteries (zone A). The shelving includes a sliding system in order to insert the batteries.
- The floor was made by plywood panels, coated with homogeneous and flame retardant PVC , edged an aluminium profile on the perimeter.
- Carrying out a side hole to pass the cables.

- The floor of the zone where the batteries are situated, is finished in steel inox.

This container has been designed with 3 separated areas: one area to place the batteries, another for the PCS and the last one kept empty.

Zone A: Empty

Zone B: PCS

Zone C: Batteries

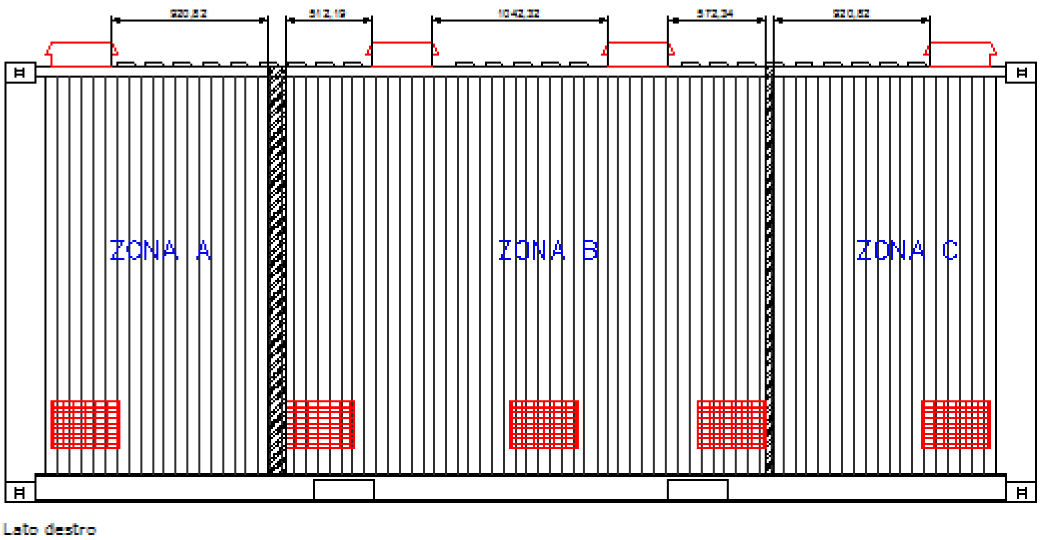

Figure 51 Division of the container in three compartments.

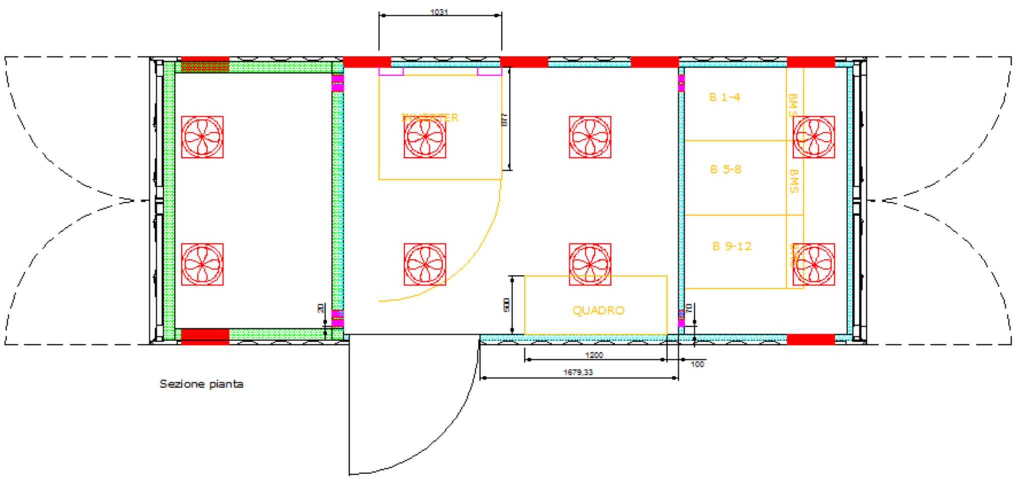

Figure 52 Section plant view of the container

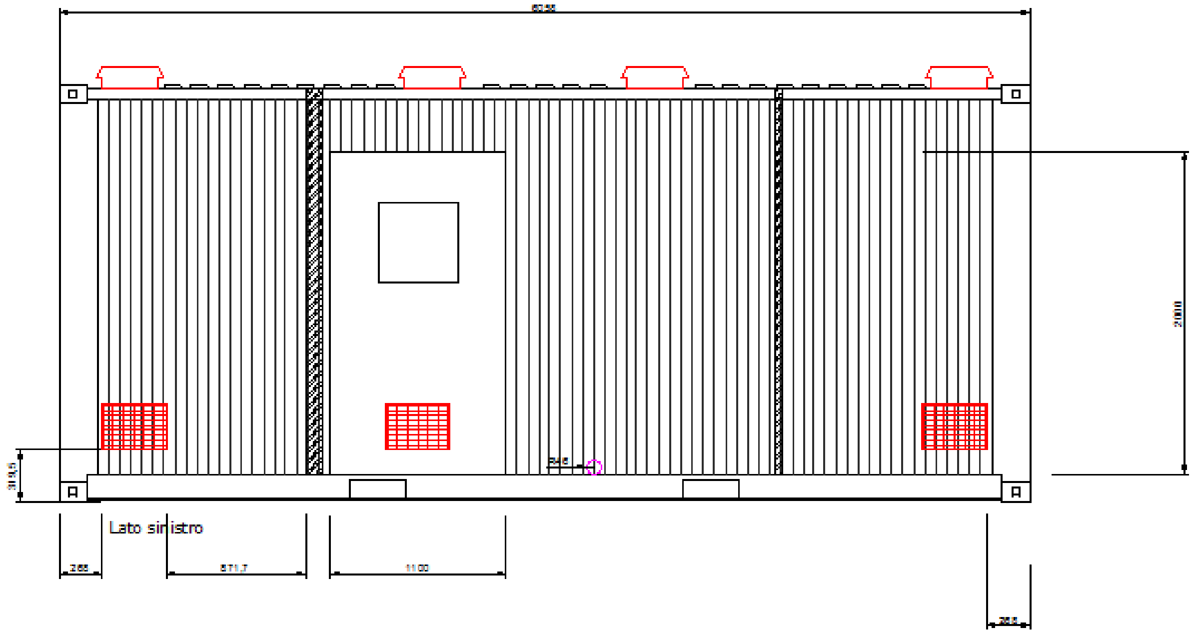

Figure 53 Left side view of the container.

Figure 54 Photo of the finished container.

9. Civil Engineering Works

In order to carry out the system, it has been necessary to modified the site. The first change has been the installation of a manhole close to the container to facilitate the passage of the cable. Besides this, the laying of power and data cables (cooper and fiber) has been carried out following the path of the existing cable ducts in the plant.

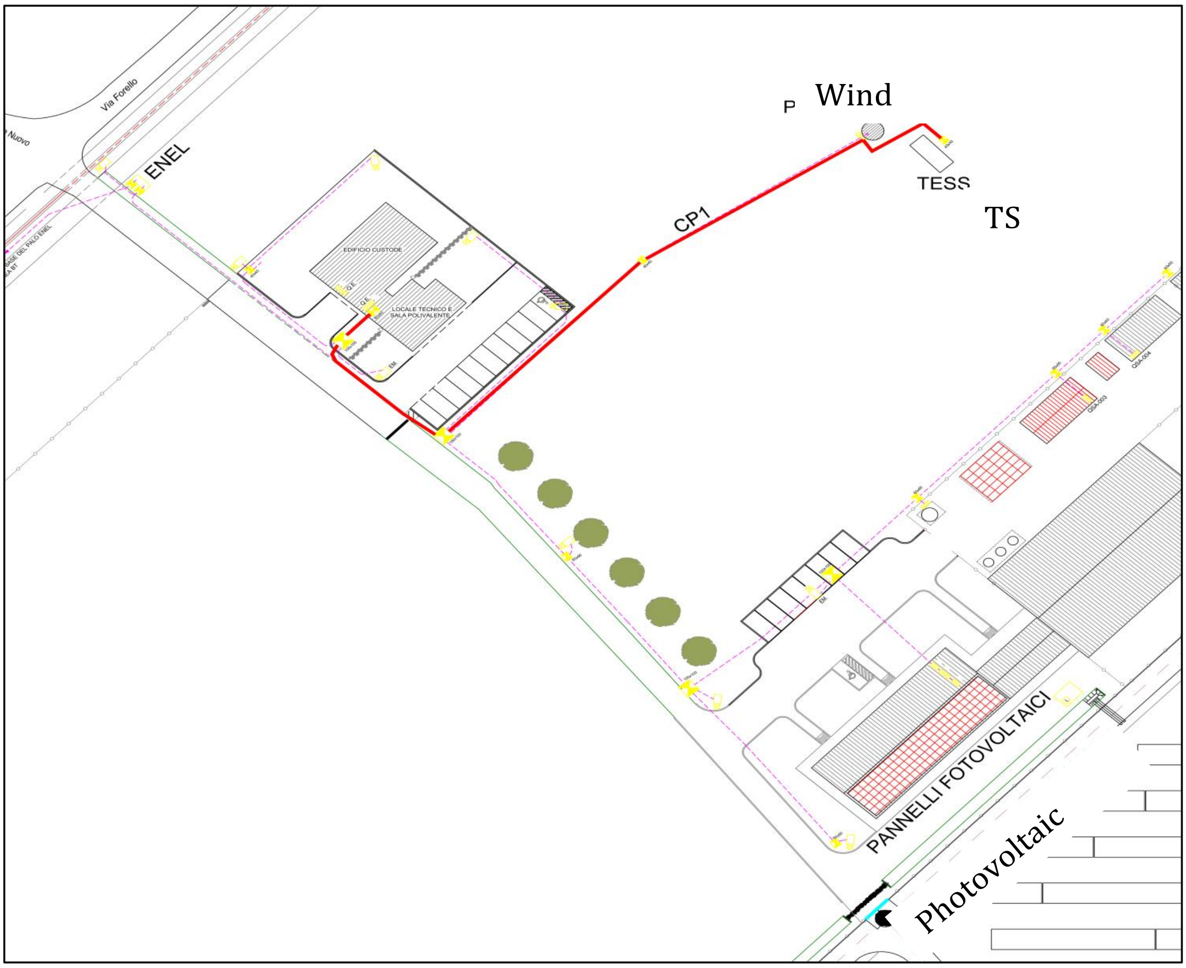

Figure 55 Planimetry of the existing cable ducts in the plant.

Cable Type	Path
Power	Container – Main Switchboard
Ground Cable	Container – WT Manhole
Copper	Container – WT Manhole
	Container – Main Switchboard
	Container – Inverter PV Plant
Fiber	Container – WT Manhole
	Container – Main Switchboard
	Container – Inverter PV Plant

Figure 56 Path of the cables laid on the plant.

It was necessary the insert of a switch of 125 A in the main switchboard in order to shut down the whole system.

Finally, the container has been located in the place which was previously chosen.

Figure 57 Photo of the container within the cheese factory.

With the installation of the container, the civil works were completed within the cheese factory.

10. Energy Storage System

Tozzi Storage (TS) is the energy storage system which:

- Optimizes the energy production from non-programmable renewable energy source, like a WT and PV, according to specific duty cycles.
- Stores energy from the grid for applications that are compatibles with TSO and DSO ones, according specific duty cycles.
- Distributes energy to the privileged and non-privileged loads when it is disconnected from the electric grid (stand-alone mode).
- Energy distribution to the grid when it is connected.
- Shows information about the process performance of the HMI through:
    - Visual message – showed on the monitor.
    - Control actions – button and keyboard.

TS consists of the following subsystems:

- BESS (Battery Energy Storage System).
- PCS (Power Control System).

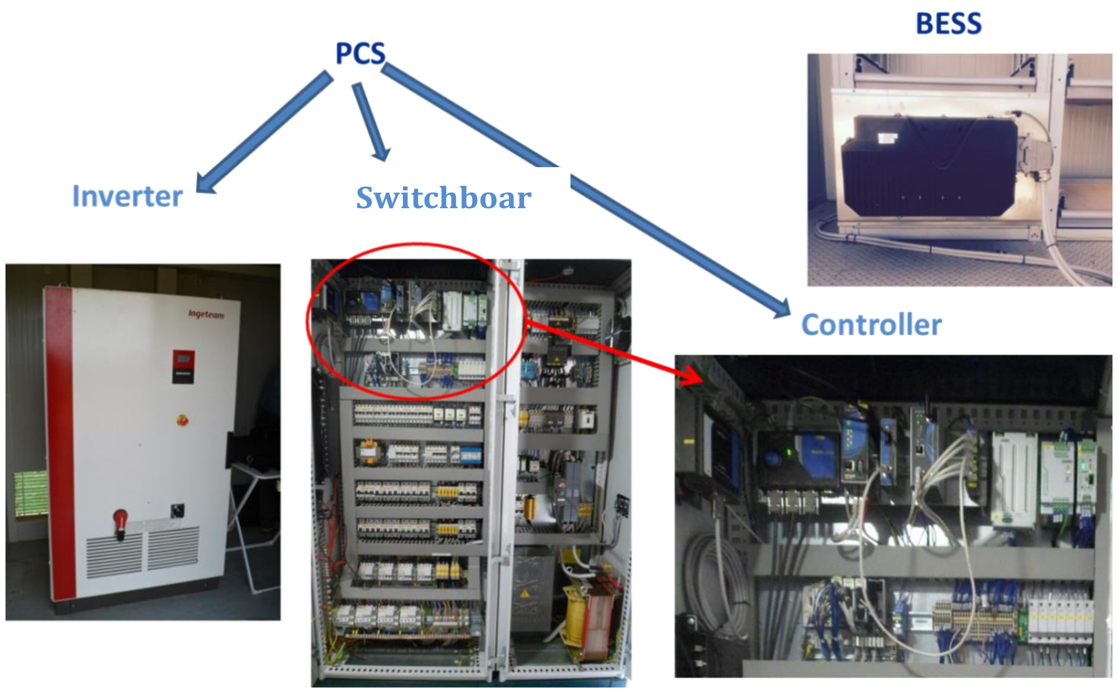

Figure 58 TS configuration.

These components are distributed within a container which is divided in three different areas.

Figure 59 TS distribution.

10.1 BESS – Battery Energy Storage System

BESS is the electronic system which consists of a battery pack and its control system named BMS.

The BMS manage the operation of a rechargeable battery (single cell or battery pack), monitoring its state, calculating and reporting the secondary data, protecting it and controlling its working ambient and/or its balance.

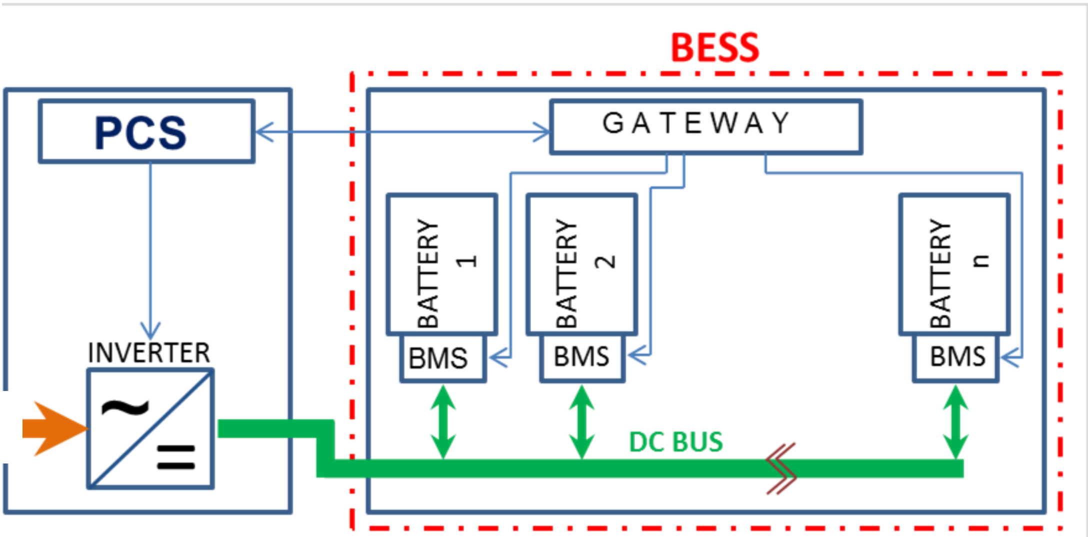

Figure 60 BESS configuration.

10.1.1 Sizing system

Once the data related to the PV plant, WT and load of the cheese factory have been acquired, it has been carried out the choice of the most suitable battery technology has been carried out according the cheese factory requirement.

The BESS must meet the following system requirement:

- Supplying energy to all the loads when the activities of the cheese factory are carrying out for at least 8 hours, without PV and WT production. The daily average consumption is around 300 kWh, therefore for 8 hours is 100 kWh.
- Covering the power peaks required by the loads. Peaks are over 30 kW.

- Storing the produced energy from the WT and PV plant. The sum of the nominal power of these two plants is 24 kW.
- Based on this requirements, the best electrochemical storage technology for this test plant has been identified. In this case, the high temperature sodium/nickel battery has been chosen.

Figure 61 Fiamm Sonick ST523 Battery.

The Fiamm ST523 battery uses a powder of nichel and NaCl as the material for the electrodes, while the electrolyte and the separator are made in β''-Al_2O_3 (good conduction of ions Na+ at T> 260°C)

2NaCl + Ni ⇆ $NiCl_2$ + 2Na, E_0=2.58V a 300°C, T = 270°C ÷ 350°C

Cathode: $FeCl_2$ o $NiCl_2$ impregnated of $NaAlCl_4$ molten (Tf =154°C), conductor of Na+ through the membrane (ηcolumbic= 100%). High safety level in case of damage.

FIAMM Sonick ST523 Battery	
Cell number	240
Nominal capacity	38 Ah
Nominal energy	23.5 kWh (efficiency 100%, DOD 100%)

Nominal power	6.25 kW
Working voltage (min/nom/max)	460/620/648 V_{DC}
Recharge Voltage (min/max)	420 V_{DC}/700 V_{DC} (via DC Bus)
Maximum discharge current	30 A
Standard time of charge	8 h
Standard time of discharge	3 h
Energy efficiency	≈ 93%
Working temperature of the ambient	from -20°C to 60°C
Working temperature	from 250°C to 350°C
Auto discharge	< 140 W per hour
Auxiliary consumption	≈ 120 W
Dimension and weight (including the BMS)	624x404.5x1007.7 cm (LxHxP); 231 kg

Table 11 Characteristics of the Fiamm Sonick ST523 Battery.

One of the main reason to choose this technology is the power/capacity ratio of the batteries and the loads requirements of the cheese factory.

Power/capacity ratio→ 1/3.

Each battery module has a power of 6,25 kW and a capacity of 18 kWh.

In this case the plant would need a pack of 8 batteries for a total of 50 kW and 150 kWh (80% DOD). In this way it satisfies all the requirements.

Another reason for the choice of this technology has been based on the low damage: These batteries do not have an explosion or fire risk, very relevant aspect as the system is sited in a transit area. Moreover, this type of batteries does not have harmful residues for the environment.

Figure 62 Battery installed into the shelf.

10.2 Overview of System Connections

The PCS interfaces to the FIAMM Battery Energy Storage System by means of a DC BUS, a communication interface to the GW and a couple of discrete signals (for safety reasons).The communication interface implemented is TCP Modbus, in which the PCS is the master and the GW is slave. This means that PCS will poll the GW for the working modes requested, the voltage/current limits, current status, and will provide the GW with some feedback signals.

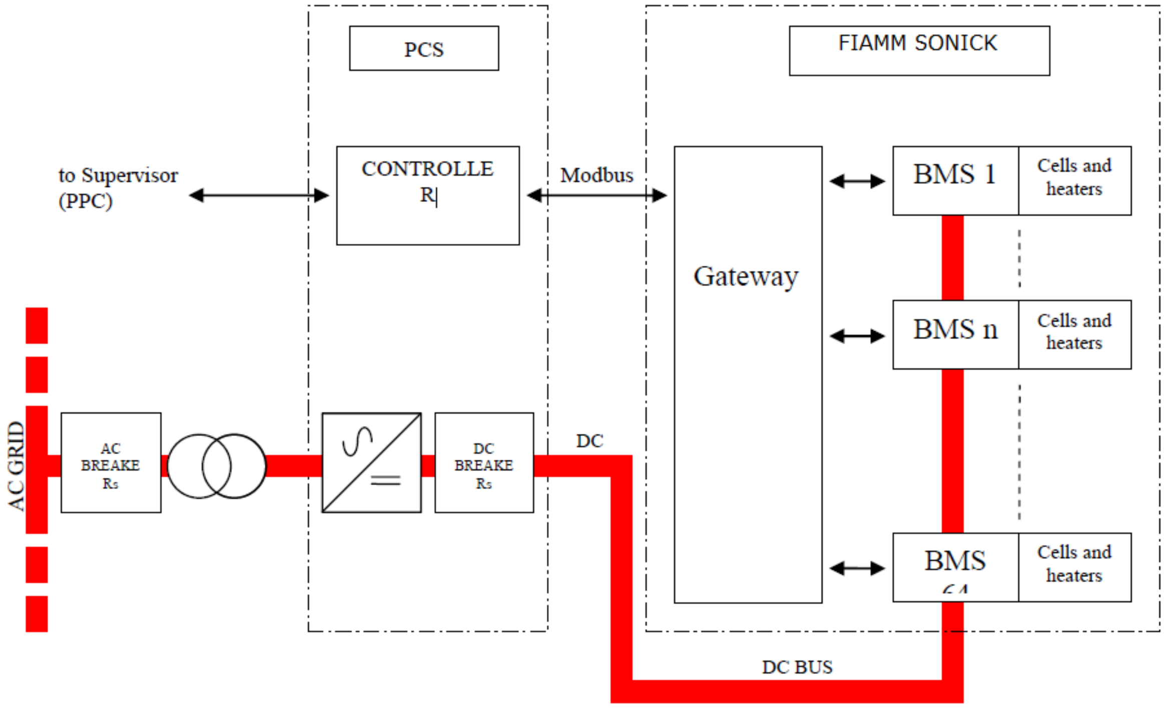

Figure 63 System connections.

The PCS must be able to bring the DC BUS voltage from 0 V to the requested value charging all the capacitors connected to the DC BUS.

At system power up each BMS has a total capacitance of about 1.5 uF connected to DC BUS. This capacitance is always connected to the DC BUS.

Below the operating temperature the BMS disconnects the battery cells from the DC BUS and activates the heaters through a PWM controller.

At operative temperature the BMS can:

- Disconnect the cells from the DC BUS
- Charge the battery cells drawing current from the DC BUS through the BMS built-in charge regulator (a diode provides a path for discharging current), provided that DC BUS voltage is above the battery voltage
- Connect the battery cells to the DC BUS to allowing the flow of charge and discharge current

10.2.1 Operation Modes

During operation, to assure proper working of the system, it is assumed that PCS can be configured in the following modes:

- STOP
- I MODE
- V MODE

In **STOP** status, the PCS is not active and **no current** is exchanged with the DC BUS. In general, the DC BUS could be at 0V or at battery voltage.

In **I MODE**, the PCS acts as a bidirectional **current generator**. The PCS sets the current according to user requests (positive or negative Power) and according to the current and voltage ranges provided by Fiamm gateway. The DC BUS voltage is determined by the batteries and is a non-decreasing function of the current (assuming positive sign for charging).

In **V MODE**, the PCS acts as a **voltage generator**. The DC BUS voltage will follow the Gateway voltage set point. The current will be determined by the batteries.

The GW requests the PCS to set a new modes using the “I MODEreq” and “V MODEreq” bits. The PCS confirm to the GW the starting of its internal transition to I mode or V mode with “I mode initialized” and “V mode initialized”, at the end of the transition the current working mode is sent by “I MODE now reached ” and the “V MODE now reached” bits.

In STOP, all IMODE=0 and VMODE=0.

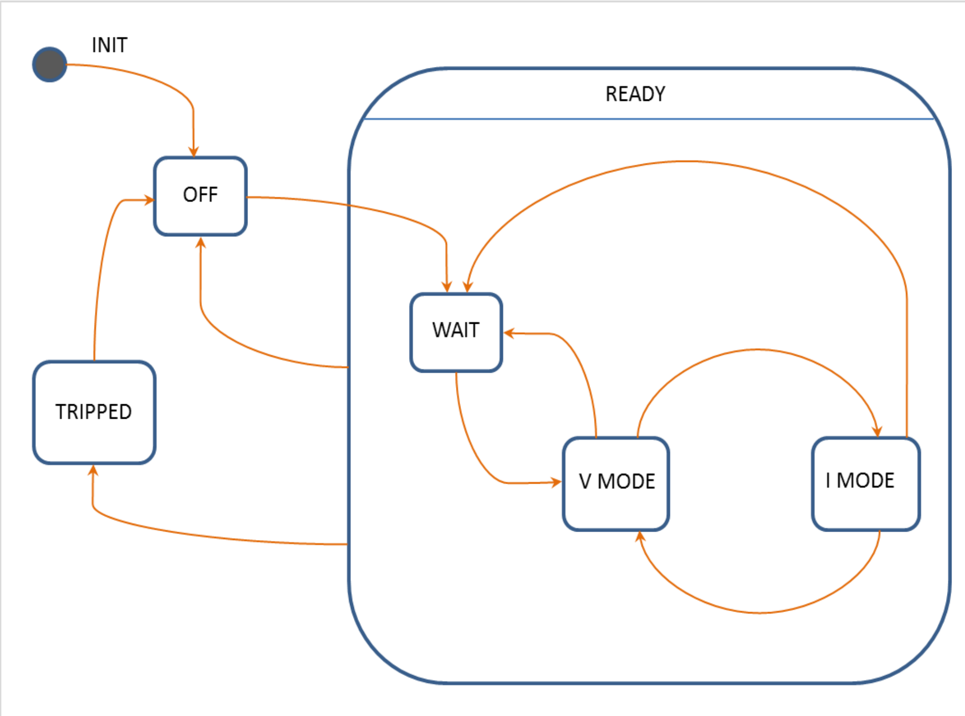

Figure 64 State diagram.

The main states of the system from the PCS point of view are:

- OFF: this state is entered at system INIT, if there is no communication with the PCS, or after a TRIP reset. It is active until the PCS.HEARTBEAT is toggled or the bit "Trip Condition Reset Request" is set to 1. It is assumed that the PCS is in STOP mode.
- READY: a valid toggling PCS.HEARTBEAT signal is received from the PCS. The Gateway toggles the

GW.HEARTBEAT reply bit and sets the GW.READY bit. There are three main sub-states:

- WAIT: In this state the both GW.IMODEREQ and GW.VMODEREQ is zero. The PCS must set the PCS.ENABLE bit to allow the transition to the V MODE state. It is assumed that the PCS is in STOP MODE.
- V MODE: In this state the PCS is in VMODE. The Gateway requests the V MODE to the PCS in order to:
    - Warm up batteries below operating temperatures

- Perform a periodical Full Charge Procedure using the BMS Built-in Charger (in one or more BMSs)
- Keep batteries warm and preventing charge or discharge
- Safeguard batteries when low SOC or high SOC limits are exceeded in I MODE
- Safeguard batteries when current or voltage limits are exceeded in I MODE

PPC Control Word allow the System Supervisor to request the activation of the V MODE

(with or without full charge). The Gateway internal logic activates the transition to the I MODE as soon as all the impeding conditions cease (see above).

- I MODE: In this state the PCS is in IMODE. The Gateway continuously monitors all battery parameters and adjusts PCS limits in order to assure safety of the system, maximizing availability in I MODE. Nonetheless, there are several conditions that activates the V MODE (see V MODE state paragraph). The Gateway estimates the remaining time before the I MODE state is left.

TRIP: this state is reached when an ALARM or a FAULT occurs. The batteries are disconnected and the “TRIP” bit is set. The PCS can try to recover from error setting the signal “Trip Condition Reset Request” to 1. If the error can be recovered, the GW goes to the OFF state. The “ALARM STATUS WORD” and “TRIP STATUS WORD” contain the description of the problem occurred. It is assumed that the PCS is in STOP MODE.

10.3 PCS - Power Control System

The PCS is the control system of the plant. It consists of three subsystems: Controller, switchboard and inverter.

10.3.1 Controller

The PCS controller is the electronic device which carries out the process functions: read all the inputs, execute the working modes previously configured and the output.

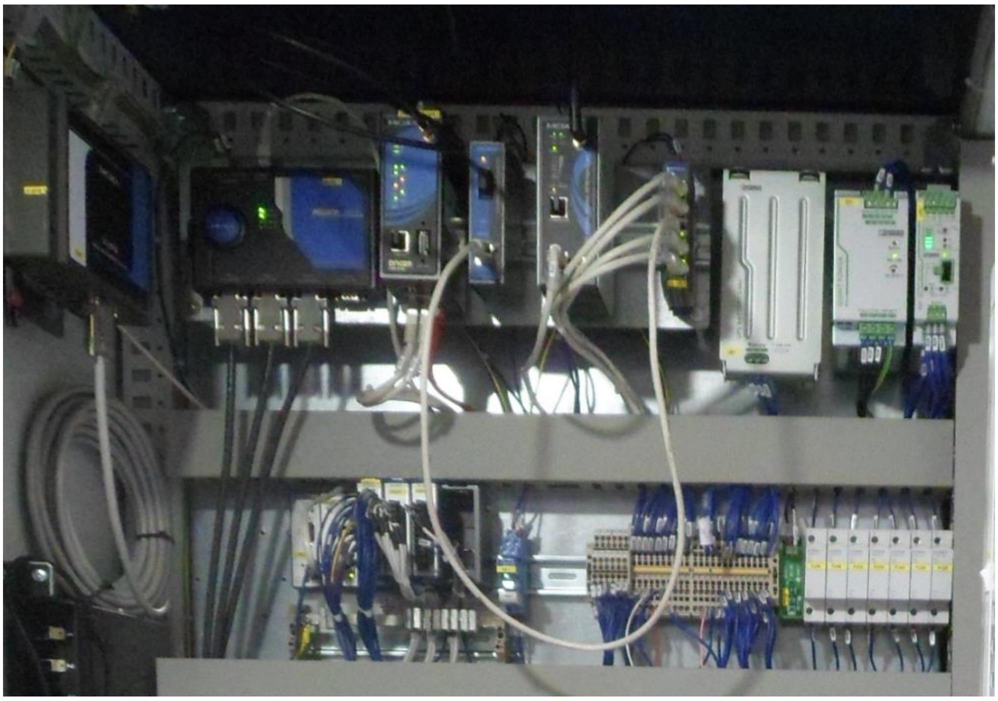

Figure 65 PCS controller.

The software used for introducing the system logic into the National Instruments hardware is LabView. The main advantage of this hardware is the possibility of carrying out types of operation that a normal PLC is not able to do.

Next figures show the synoptic of the software modules implemented in the controller.

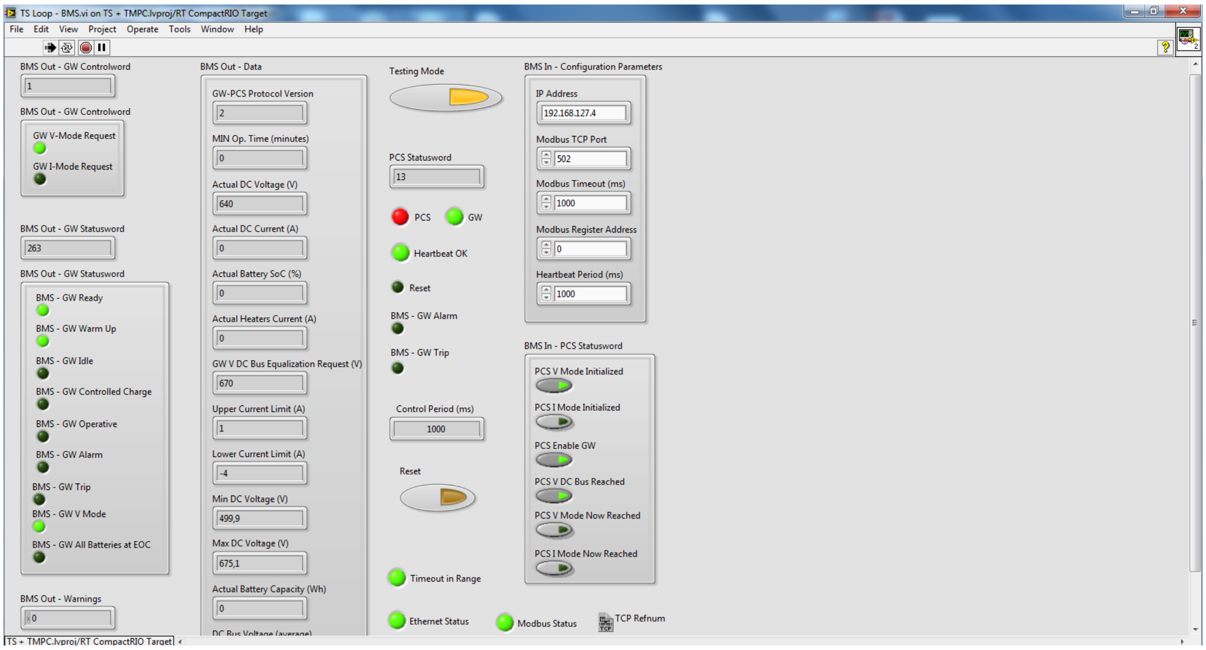

Figure 66 Interface between PCS and BESS.

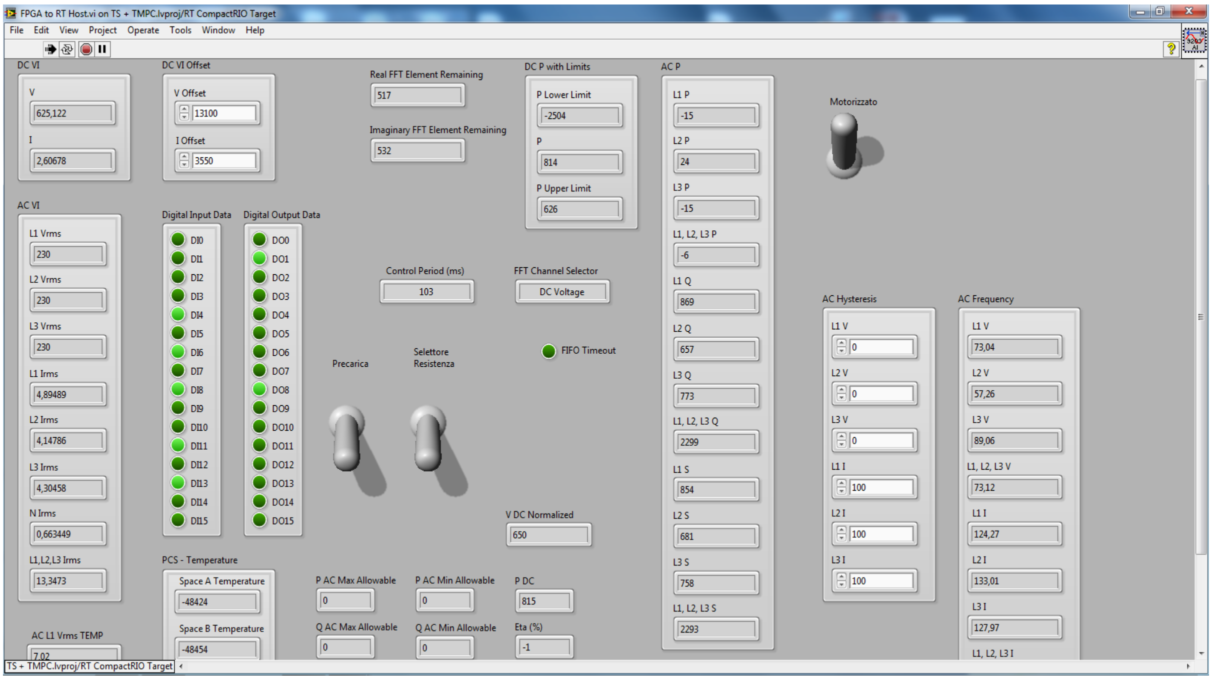

Figure 67 Interface of management of the analogue and digital input/output.

Figure 68 Interface between PCS and inverter.

10.3.2 Switchboard

The Switchboard has been designed to satisfy the requirement of the electric system.

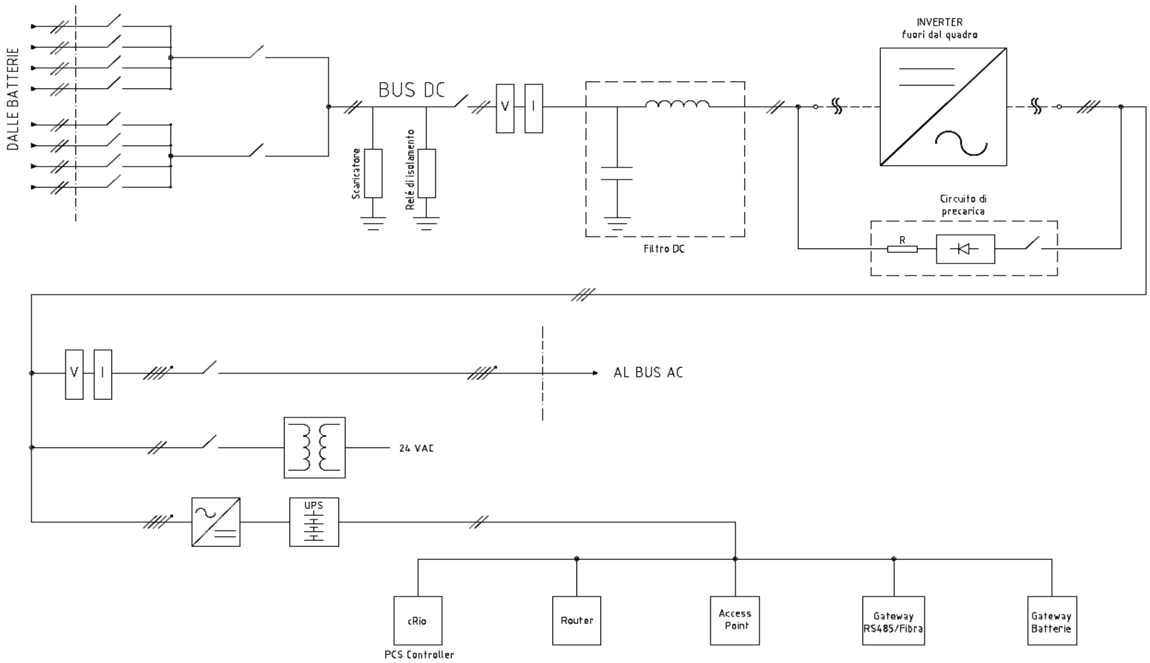

Figure 69 Functional system diagram.

The switchboard is divided in two parts; DC and AC sections.

- DC Section

  This section consists of different components, which are described below.

  - Protection and battery switch

    The batteries of the subsystem are isolated from the ground and individually protected by two fuses in case of overcurrent. Moreover, they can be switched manually by means of switches in order to be serviced.

    The switches are equipped with auxiliary contact in order to PCS reads its state.

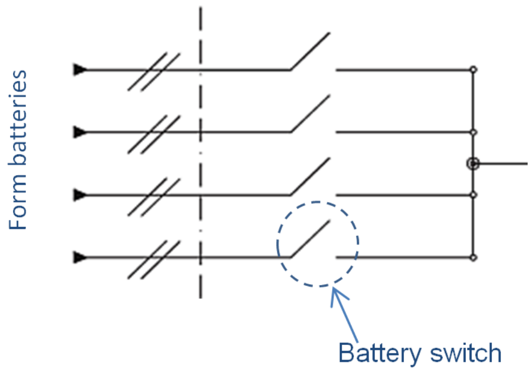

Figure 70 Battery switch

  - String bus

    The batteries of the subsystem are gathered in switching strings manually and protected by thermomagnetic switches.

    The switches have an undervoltage release which have the function of opening the switch in an emergency case.

    The switches have an auxiliary contact to allow the PCS Controller see the state.

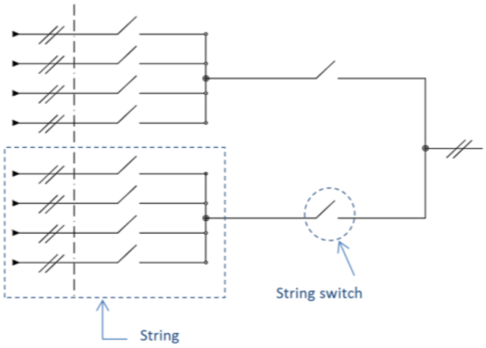

Figure 71 String switch.

- Voltage and current measurement

  The DC bus of the system is equipped with analogic sensors to measure the local voltage and current. In this way the PCS controller can manage the operation cycle of the system.

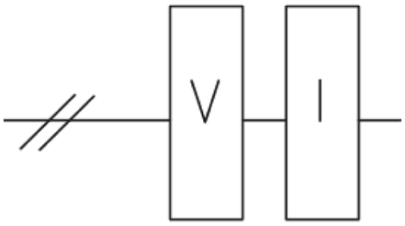

Figure 72 Voltmeter and ammeter.

- Overvoltage protection

  The subsystem is equipped with a discharger which has the function of protecting the DC bus from any overloads. This discharger has an auxiliary contact to allow the PCS controller to know the state.

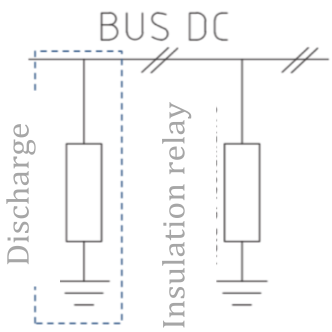

Figure 73 Overvoltage Protection.

- Isolation control

  The subsystem is equipped with a monitoring relay which has the function of communicate to the PCS controller any loss of isolation. This monitoring relay has an auxiliary contact to allow the PCS controller to know the state.

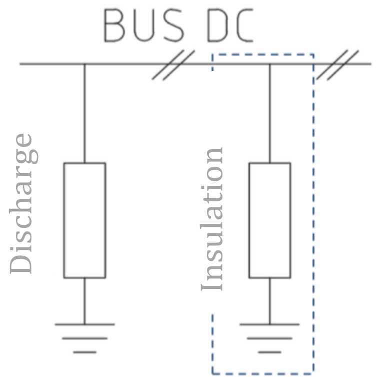

Figure 74 Insulation relay.

- Pre-charge circuit

  The subsystem is equipped with a pre-charge circuit which has the function of absorb the peak initial current.

- Capacitive load of the BTS

  The system manage a capacity of 1,5 μF per battery in the DC bus. In the case of 8 batteries this value is 12 μF.

  The circuit is driven by the PCS controller.

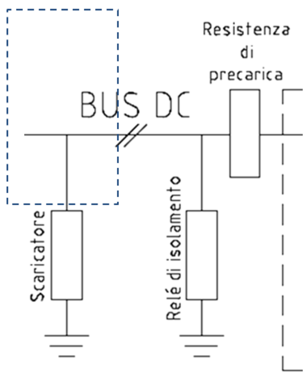

Figure 75 Capacitive load of the BTS

- DC bus filter

  The DC bus of the subsystem is protected from interferences from the inverter by means of a low-pass LC filter with pass-band lower than 40 Hz.

  The capacitive part is gathered to the discharge resistance in order to guarantee the discharge of the remaining energy when the switchboard is opened.

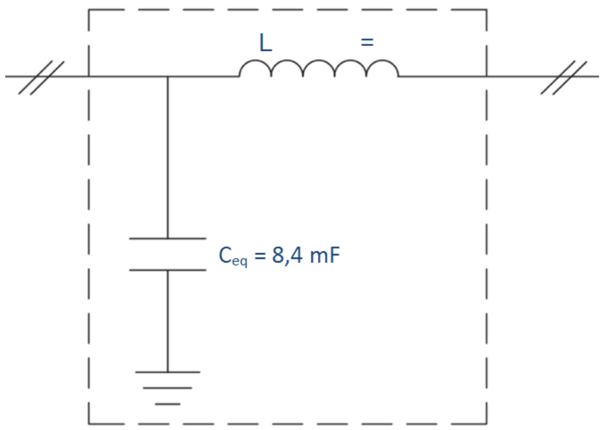

Figure 76 DC filter.

- Ac Section
  - Power supply of the BMS

  The subsystem is equipped with a transformer circuit of the power supply from 400 V AC to 24 V AC, necessary for the auxiliary components of the high temperature batteries.

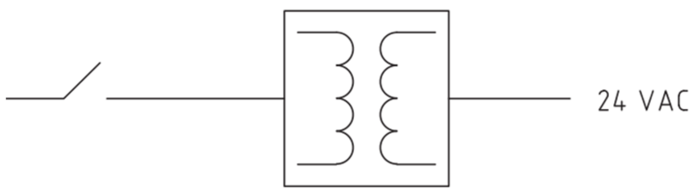

Figure 77 Circuit of the transformer.

- Power supply emergency

The subsystem is equipped with a circuit which supply the emergency circuit (24 V DC UPS) to the PCS controller when there is no voltage in the grid. In this case, the PCS controller takes the system to a safe state.

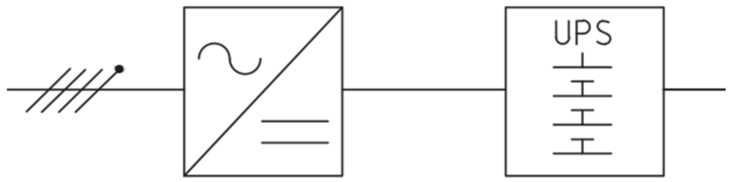

Figure 78 Power supply emergency.

The AC bus of the system is equipped with analogic sensors to measure the local voltage and current. In this way the PCS controller can manage the operative cycle of the system.

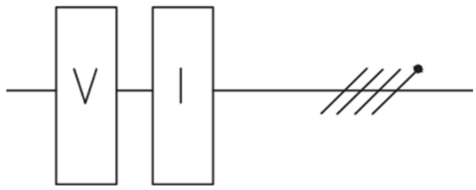

Figure 79 Voltmeter and ammeter.

- Protection and bus AC switching

The bus Ac of the subsystem can be switched manually by means of thermomagnetic switch of protection.

The switch has an undervoltage release which have the function of opening the switch in an emergency case.

The switch has an auxiliary contact to allow the PCS Controller see the state.

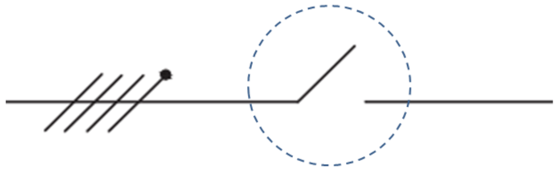

Figure 80 Protection switch.

Also the switchboard is equipped with the following auxiliary services.

- **Temperature monitoring:** the subsystem is equipped with temperature sensor appropriately positioned to allow the PCS controller to map the thermal state of the environment.
- **Temperature Management:** the subsystem is equipped with independent thermostats from the PCS controller in order to switch on the forced ventilation subsystem with the goal of guaranteeing a constant temperature in the three areas of the container.
- **Interior Illumination:** the subsystem is equipped with lamps and its switches to light all the components of the switchboard. Also, the area with the batteries have an illumination system.
- **Emergency illumination:** the subsystem is equipped with a thermomagnetic switch for the control of the emergency illumination of the area inverter.
- **Auxiliary power supply plug:** the subsystem is equipped with a monophase plug for supplying external devices.
- **Auxiliary ethernet plug:** the subsystem is equipped with an auxiliary ethernet plug for connecting digital external devices.

Figure 81 Switchboard.

Figure 82 Main switch with two voltmeters, AC and DC.

Figure 83 Selector switch of AC measurements and lamps of voltage warning.

10.3.3 Inverter

PCS inverter is the power electric converter which transforms direct current (DC) into alternate current (AC); the AC can be converted into any voltage and frequency through suitable transformers, commutators and control circuits.

Figure 84 Inverter Ingeteam.

- Operation mode
  - Wait for the set point of the working parameters from PCS controller, P_{sp} and Q_{sp}.
  - Activate the commands received by the PCS Controller with immediate effect that is, starting the execution before 50 ms from the receipt of the command.
  - Set P and Q values between the nominal and the maximum, for a time is not greater to the minimun between t_{inv} and t_{batt}: $t < \min(t_{inv}, t_{batt})$ after which the inverter has to return to the nominal condition automatically.

- It is put in phase with the AC bus when is supplied by the grid in nominal conditions.
- Change its frequency.

- LVFRT/HVFRT

The system integrates the LVFRT algorithm according to the CEI 0-21 and CEI 0-16 Ed.III and BDEW

- Failure management

The system is equipped with a diagnostic function of the run-time regarding the critical function. The system is disconnected in case of failure opening the AC switch.

11. Master Power Control

The Tozzi Master Power Control (TMPC) is the management system of the plant, consists of monitoring electronic devices.

The characteristics and functions of the TMPC are described below.

- **Management and monitoring system.**

  The subsystem carries out the management and monitoring off-site.

- **Data acquisition.**

  The subsystem is equipped with control functions of the data acquisition:

  - Enable/disable and scanning of the analogic/digital inputs.
  - Entering data manually.

- **Data communication.**

  The subsystem is equipped with control function of the port and the communication protocol.

- BIST and troubleshooting.
- The subsystem is equipped with BIST functions and troubleshooting driven by the identification and signposting of the failure:
  - Execution Flow.
  - Control function.
  - Function of the diagnosis and state of health.

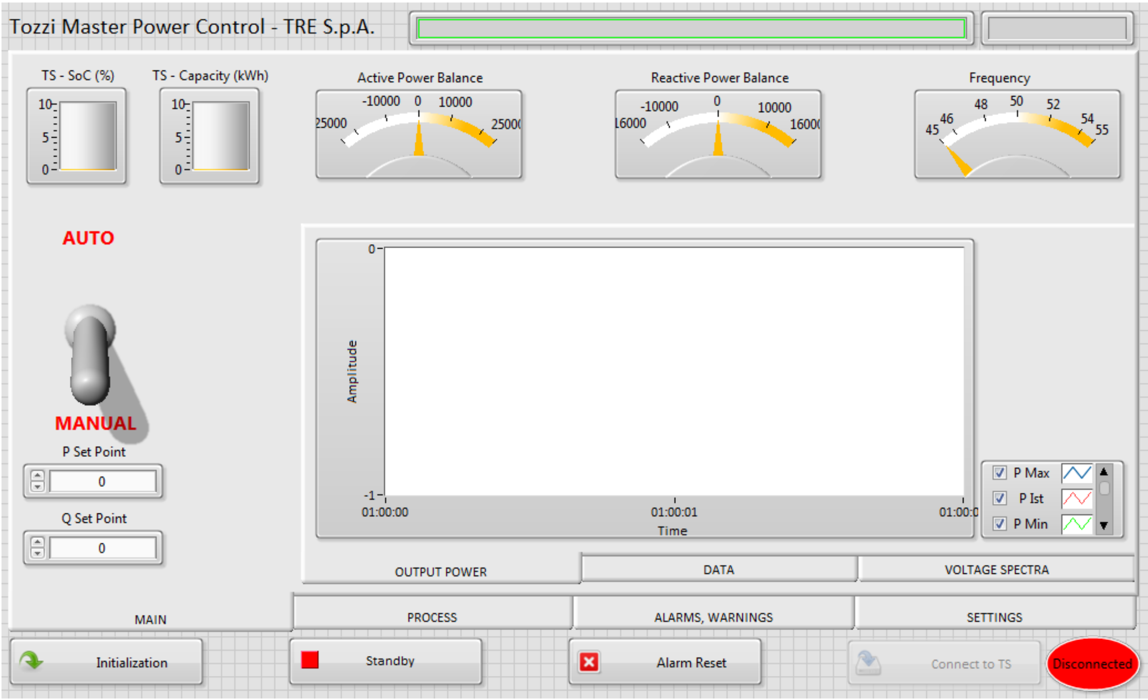

Figure 85 Screen of the start of the system.

The different duty cycle that the TMPC manages are described below.

- Charge.

  The system runs different charge profiles:

  - Complete: it is used for the recharging balance. It indicates a charging phase characterized by a change in the rise of the SOC up to 100%.
  - Continuous: It is the Nominal operation recharge. Indicate an operation characterized by a charge phase without phase interpositions of stand-by or discharge phase.
  - General: Charging out the previous range, in this case the limits of current absorption are fixed from the physic limits of the batteries.

- Discharge.

  The discharge profile is characterized by:

  - Minimum current discharge regarding to the maximum available time of the system.
  - Maximum current discharge regarding to the maximum available time of the system.

The different applications that the TMPC manage are described below.

- **Optimization of the energy production from RES.**

  The system stores in the TS the energy overproduction from RES in relation to the needs of the load consumer, avoiding the transmission curtailment.

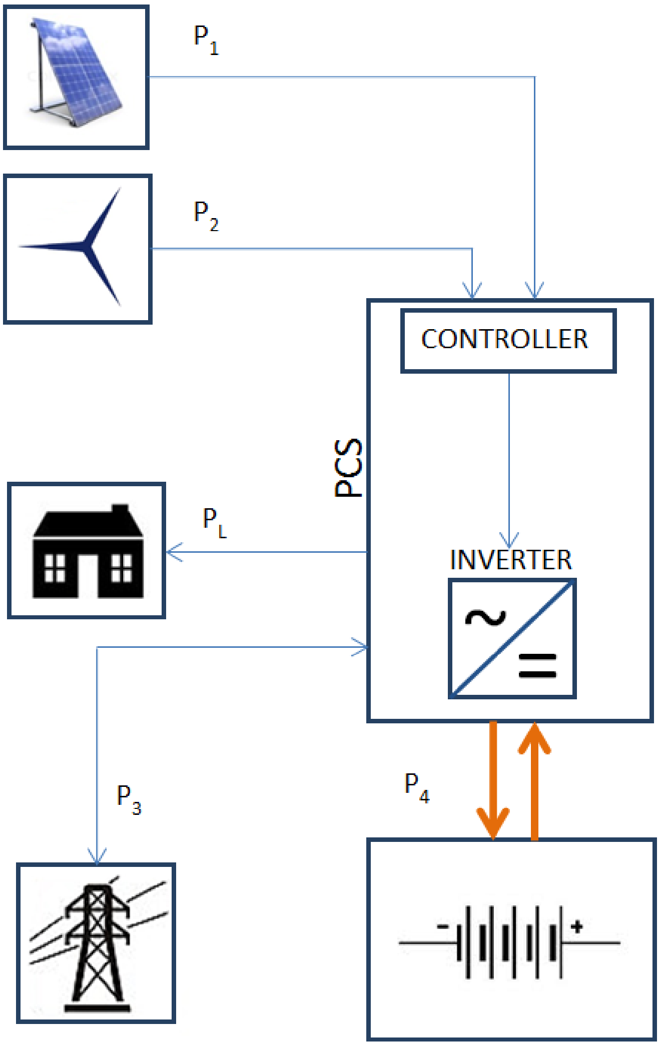

Figure 86 System configuration.

The energy flows are detailed bellow.

$$
-\begin{cases} P_1 + P_2 \geq P_L & \Rightarrow \; charging\ process \\ P_4 = P_1 + P_2 - (P_L + P_3)\,, & up\ to\ \ SOC = 90\% \\ I_4 = (I_1 + I_2) - (I_L + I_3) & \end{cases}
$$

$with:$

$$\begin{cases} V = 640V = costant \\ I_4 \leq I_{max} = 15A = maximum\ charging\ current \end{cases}$$

If we are in F1 Enel (energy price based on the ENEL phase, F1, F2, etc…), it is advisable to carry out the normal cycle and the surplus introduced into the grid.

$$- \begin{cases} P_1 + P_2 \leq P_L & \Rightarrow \ Discharging\ process \\ P_3 = P_1 + (P_2 - P_L), & \quad up\ to\ SOC = 10\% \\ \ I_4 = I_L - (I_1 + I_2 + I_3) & \end{cases}$$

$with:$

$$\begin{cases} V = 640V = costant \\ I_4 \leq I_{max} = 50A = maximum\ discharging\ current \end{cases}$$

- **Peak shaving/valley filling**

In this application, the system follows continuosly the peak/drop of production from RES absorbing/supplying the power in excess/deficit regard to the energy demand. The system acquires data at high frequency by means of the TGA and the analogic sensors. Moreover it predicts the time of maximum consumption according to the specific load curve of the load consumers.

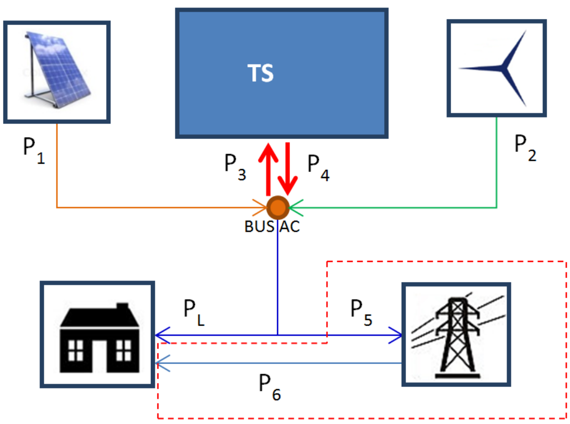

Figure 87 Peak shaving/valley filling configuration.

The energy flows are detailed bellow

$$If\ P_1 + P_2 > P_L \Rightarrow \begin{cases} P_3 = (P_1 + P_2) - P_L \\ P_4 = 0 \end{cases} \qquad PS$$

$$If\ P_1 + P_2 \leq P_L \Rightarrow \begin{cases} P_4 = P_L - (P_1 + P_2) \\ P_3 = 0 \end{cases} \qquad VF$$

- **Stand alone**

The system optimizes the energy production from the RES and manages the loads, according the scheme below.

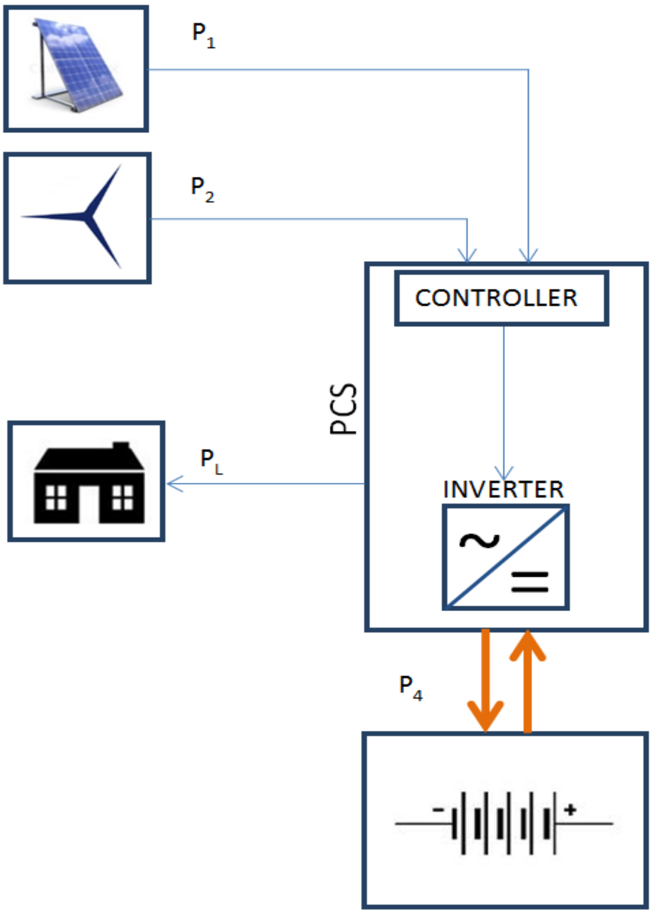

Figure 88 Stand alone configuration.

The energy flows are detailed bellow.

$$
- \begin{cases} P_1 + P_2 \geq P_L & \Rightarrow \ charging\ process \\ P_4 = P_1 + P_2 - (P_L + P_3)\ , & up\ to\ \ SOC = 90\% \\ I_4 = (I_1 + I_2) - I_L & \end{cases}
$$

$with$:

$$
\begin{cases} V = 640V = costant \\ I_4 \leq I_{max} = 15A = maximum\ charging\ current \end{cases}
$$

$$
- \begin{cases} P_1 + P_2 \leq P_L & \Rightarrow \ Discharging\ process \\ P_4 = P_L - (P_1 + P_2), & \quad up\ to\ SOC = 10\% \\ \quad I_4 = I_L - (I_1 + I_2) & \end{cases}
$$

$with$:

$$
\begin{cases} V = 640V = costant \\ I_4 \leq I_{max} = 50A = maximum\ discharging\ current \end{cases}
$$

- **Energy reserve**

  The TS works at SOC 50% to keep a capacity reserve in case of underproduction RES and a recharge margin in case of overproduction. In this case the system behaves as a lung with the ability of expanding and contracting around the state of semi-charge depending of the generation level of the RES.

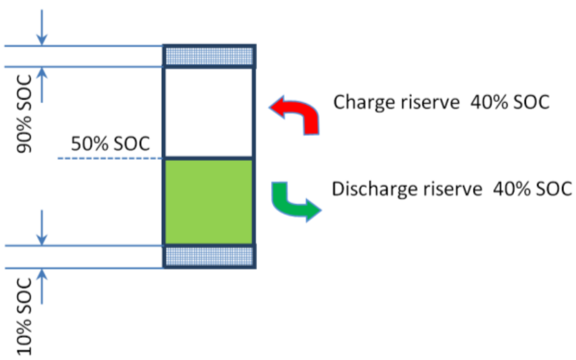

Figure 89 Energy reserve configuration.

- $For\ 10\% \leq SOC \leq 40\% \Rightarrow Charge\ process$

$$\begin{cases} V = 640V = costant \\ I \leq 50A = maximum\ charging\ current \end{cases}$$

- $For\ 40\% \leq SOC \leq 90\% \Rightarrow discharging\ process$

$$\begin{cases} V = 640V = costant \\ I \leq 15A = maximum\ discharging\ current \end{cases}$$

11.1 TGA – Tozzi Grid Analyser

This is the acquisition instrument of electrical data of the system. The main functions are the following:

- **Analyse of the grid parameters**

  The system measures the following mono-phase / three-phase grid parameters.

  - Phase-Neutral Voltage (V).
  - Phase-Phase Voltage (V).
  - Current (A).
  - Active Power (W), reactive power (VAR), apparent power(VA).
  - Power factor cos(Φ).
  - Harmonics voltage (V) and harmonics current (A).
  - THD (%).
  - Frequency (Hz).

- **Voltage measurement**

The system acquires the voltage values by means of interior process unit connected to the grid cable.

- **Current measurement**

The system acquires the current values by means of three amperometric transformers connected to the interior process unit.

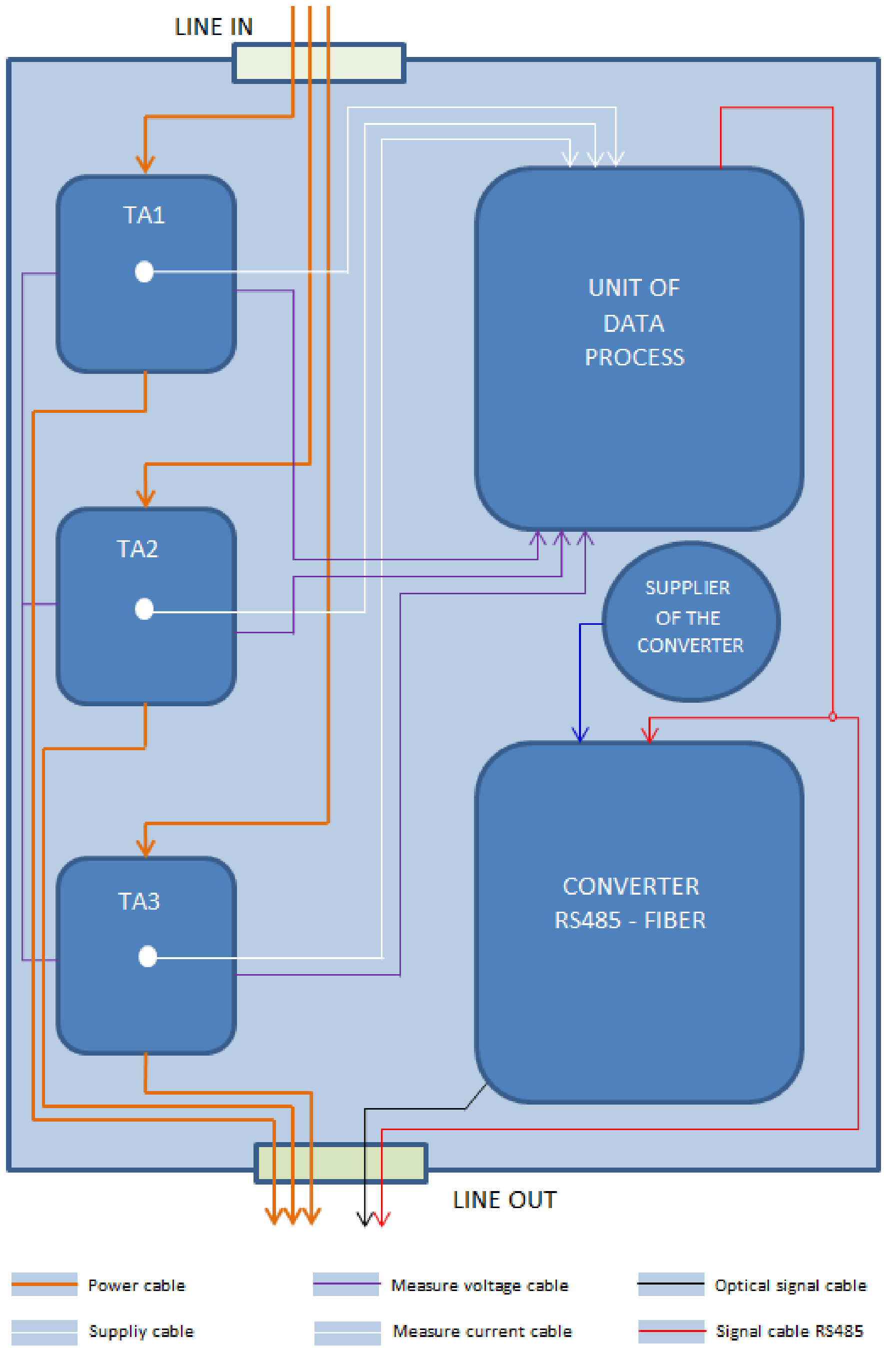

Figure 90 System block diagram.

The system communicates throug the serial port RS485 or fiber, with a protocol of communication Modbus/RTU Slave for the data transmission to the PCS controller.

Figure 91 TGA installation.

12. Communication

The TS can be managed remotely through the use of a modem/router HSPA which has been installed in the interior of the switchboard or accessible on-site through an Access Point.

The different subsystems communicate with each other as it is described below.

- **Communication between PCS controller and PCS inverter**

  The subsystem communicates with the PCS inverter by means of an Ethernet connection.

- **Communication between PCS controller and BESS**

  The batteries are connected by CAN BUS to a Gateway and this one to the PCS controller through Ethernet using an intermediate switch.

- **Communication between TMPC and TGA**

  The TGAs communicates with the TMPC by means of two different channels:

  - Transmission copper cable: the TGAs are connected through RS485 to the Gateway (sdfsdf, 234)and this one to (gdfgdfg) the TMPC through Ethernet using an intermediate switch.
  - Transmission fiber cable: the TGAs are connected to the TMPC through a fiber ring and a converter of fiber to RS485

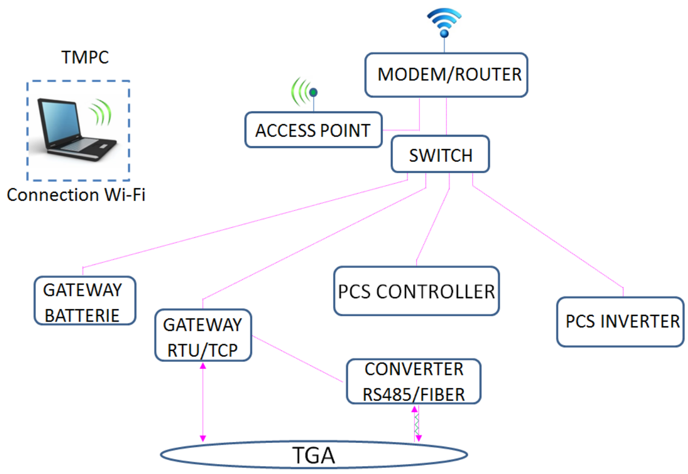

Figure 92 Communication block diagram.

13. First tests

Once the test plant has been placed and all its components assembled, we proceeded to test system functionality and the application described in the previous chapter. In particular, the application tested was “optimization of the energy production from RES”.

Due to delays in the supply of batteries, at the present moment only one has been installed. We could proceed with the test plan anyway, despite the impossibility to operate the storage system at full capacity.

Ahead of the application test, it was necessary to test each system component. This test lies in switching on the system and set it to the operation mode (“I mode”). The different steps are described below.

Firstly, the switches of the switchboard were rotated to “on” position, (see Figure 81 and Figure 82) then it was carried out the same operation with the switch of the inverter (the switch is necessary to rotate only once, then, the inverter will be “on” or “off” depending on the presence or absence of current in the system).

After this step, the battery pre-charge operation starts, giving voltage to the DC bus up to a value approximated of 580 V. Then, the electronic boards of the inverter are turned on and the communication check starts in order to control the state of the system components. If there are no communication problems, the inverter pass to magnetization mode and it is connected to the grid. The PCS changes the operation mode of the inverter to voltage mode and gives a set point around the 105% of 580 V with the scope of opening the pre-charging circuit. When the DC bus voltage has been raised, the pre-charging circuit is disconnected.

Afterwards, the inverter reads the state of the batteries from the BMS and communicates that it has changed to “V mode”. Thereby, the battery begins the warm-up operation for 12 hours. Once the batteries have reached the operation temperature, the BMS communicates to the PCS that it is ready.

Finally, the inverter changes the mode to “ I mode” (operation mode), in this way the system is ready to work.

13.1 Optimization of the energy production from RES.

The TMPC is the management system of the plant and the responsible of setting up the operation mode. In this case, the system has set up the values for the optimization of the energy production from RES.

Initially, the TMPC by means of the TGA acquires the power production data from the WT and PV plant and the power consumption of the load cheese factory.

There is a tool in the TMPC that allows the data exportation to an Excel file in order to analyse them later. The TGA was set up for carrying out measures each 200 ms.

In Figure 93, a large difference is noted between production and consumption, but equally there are moments where the sum of the WT and PV production is bigger than the consumption. This implies that part of the production must be introduced into the national grid. Due to this fact, the goal of this application is the use of all the energy production to satisfy the energy demand. The plot of these data is showed below.

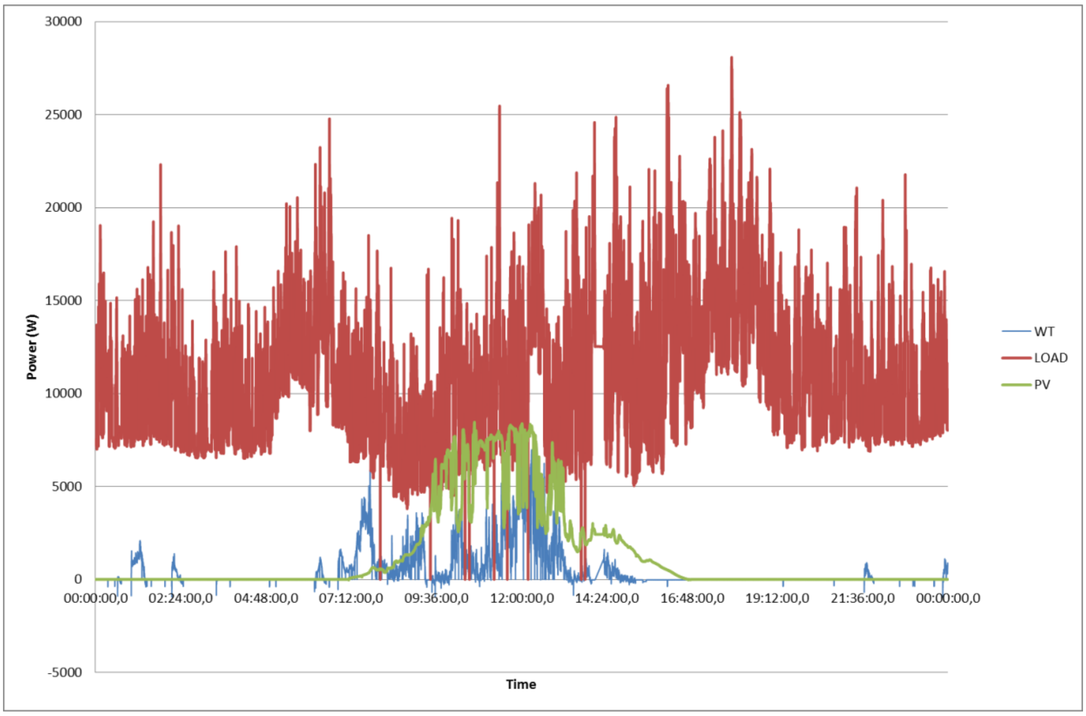

Figure 93 Energy production from the WT and PV plant and the energy consumption of the load cheese factory on date 12/11/2014

Once the TMPC has analysed the data, it sends the inputs to the PCS controller in order to balance the power. Afterwards the TMPC shows the progress of the plant activity.

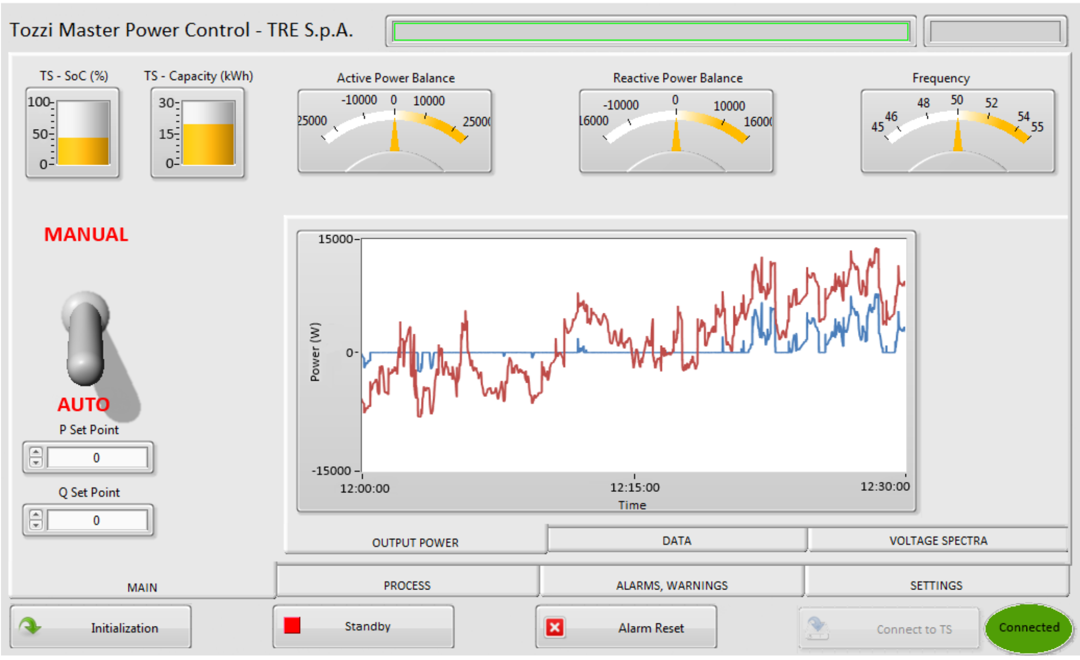

Figure 94 Snapshot of the plant activity for a period of 15 min.

In line red $P_{Grid} = P_{Load} - P_{WT} - P_{PV}$

In line blue $P_{Grid} = P_{Load} - P_{WT} - P_{PV} - P_{TS}$

This Figure 94 shows the trend of the energy consumption from the grid (red line) and the trend of the real consumption (blue line) using the TS. In this way, we noted how the peaks are reduced to 0, as long as they are in the range of [-6,6] kW. This range is defined for the maximum charge/discharge power of the TS, that in this case is 6 kW due to the presence of just one battery. Even so, there are periods where the energy consumption/supply from grid is 0, which was the purpose of this application.

This energy balance of the plant is near 0 as it is shown in the snapshot of the TMPC because of the minimum system threshold which is approximated [-25,25] W (see Figure 95)

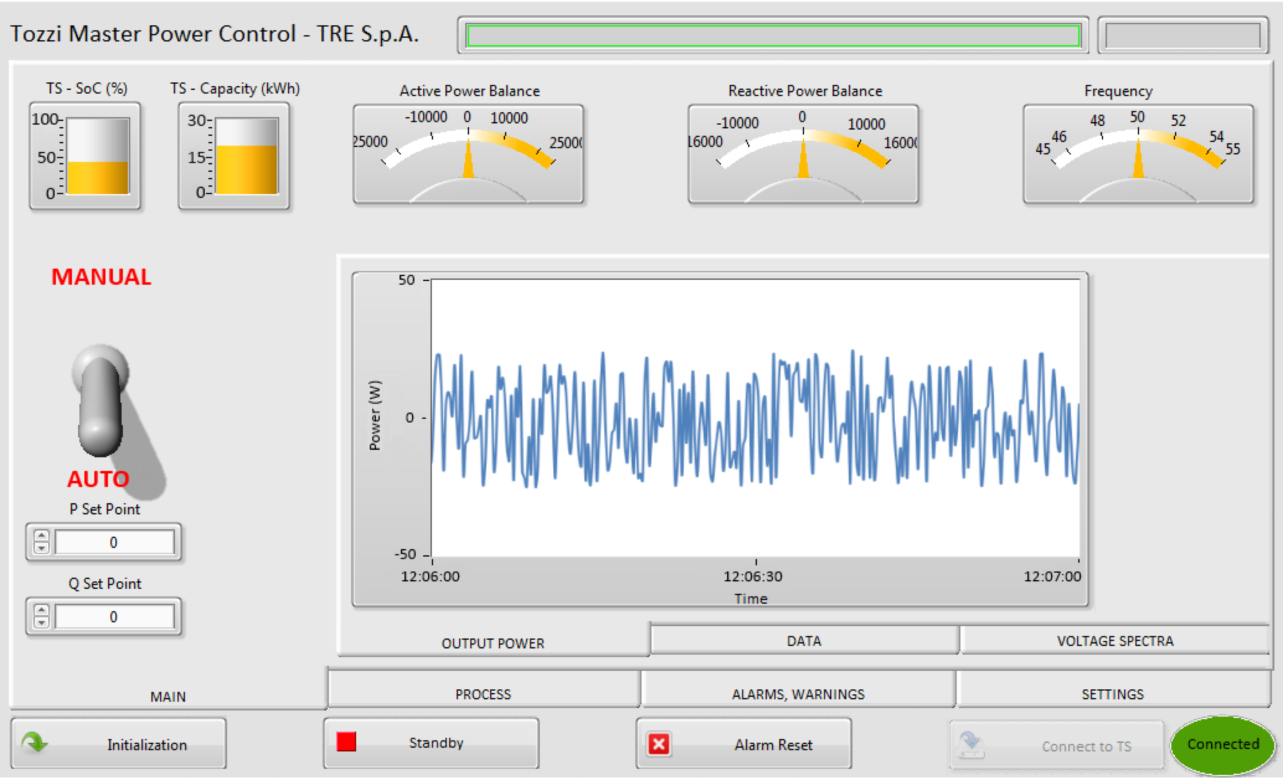

Figure 95 Snapshot of the TMPC where is showed the noise in the grid.

14. Conclusions

A microgrid was created within a cheese factory where a 7 kW WT and a 17 kW PV plant were already present. A storage system, TS (Tozzi Storage), was designed, developed and installed in order to manage the energy flow from the RES to the loads. The TS is composed by the following two subsystems: BESS and PCS. With the aim of monitoring the power flows, a TGA was also designed, constructed and connected to the wind turbine, photovoltaic plant and the load switchboard.

Different electrochemical storage technologies were studied, and by taking into account the load requirements of the cheese factory, we identified the high temperature salt Na-$NiCl_2$ battery technology as the most suitable solution.

The data acquisition in the load analysis indicates the need of a 30 kW battery system, but nowadays the system is composed by a single battery of 6 kW. Shortly, by introducing more battery modules, the target value of 30 kW will be reached in order to satisfy the total load demand of the cheese factory.

Different tests were carried out to verify the good performance of the battery, especially in the most critical charge and discharge phases. The battery met all the specifications declared in the data sheet.

The condition to optimize the use of RES was tested with success. It was demonstrated how the integration of the TS reduce or in some cases eliminate the consumption or supply of energy from the grid.

Also, the system has been realized to be flexible, that is, it can be installed in different places with different system architectures through a modification of the TMPC configuration and the installation of the TS.

Further work is planned, as in the near future the off-grid operating condition will be tested once the system is completed with the remaining batteries.

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