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Master's Thesis in Electrical Engineering

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Analysis of Battery Energy Storage Systems and Preliminary Design Based on Insights from Real Case Studies by Iren S.p.A

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Abstract

Originally conceived as a support tool for renewable energy sources, storage systems have evolved into a versatile and valuable technology with applications across a wide range of energy environments. This work begins by introducing the concept of energy storage systems, outlining their various functions and roles within modern energy infrastructures. The main focus will be on Battery Energy Storage Systems(BESS) and the manifold applications developing in recent years.
After discussing the future role of BESSs in frequency regulation and what that regulation actually comprehends, the focus will move on exploring real-word implementations carried out by the energy company Iren in the piedmont and lombardy region. There will be presented two particular storage systems: one implemented at the Turbigo facility and one installed at Moncalieri facility, which I had the opportunity to visit. Both of the BESSs are entrusted with many roles in support to the thermoelectric power plants that models their structure and managment.

Building on the insights gathered, the final aim of this thesis is to propose, even at a conceptual level, the design of an additional storage system for the Turbigo thermoelectric power plant. The BESS proposed is suppose to unite with the storage system already installed with the intention to assist in frequency and voltage regulation at the facility, as well as possibly helping with the startup of the plant.

The design process will consider components from battery stacks to the transformer, ideally following the technical standards of a preliminary engineering design, and will culminate in the development of a unified schematic for the proposed system presented using the software AutoCAD. This program was already utilized by the clients to design other electrical diagrams and structures, so the hope is to summit a work usable in the developing and installation of the BESS, in order to facilitate the work of the future assigned engineers on the project.

1 Energy Storage Systems

Energy storage system refers to a system able to store energy in various forms, on a temporary basis, and release it on demand. This principle as simple as it is has slowly revolutionized the energy landscape. It was a system created to be supportive of unreliable or inconstant energy sources such as renewables, but with time its applications have increased as have the various technologies to achieve them.

Pairing a renewable energy plant with a storage system makes it possible to ensure electricity supply even when production is not feasible or when the load demand cannot be met. This integration helps balance supply and demand, improving the reliability of the electrical service. From this example alone, it is evident that one of the key strengths of storage systems lies in their ability to provide flexibility to the grid. Both large and small storage facilities can support grid stability by supply energy or storage in response to hourly or seasonal fluctuations in electricity demand. In the event of network congestion or transmission problems, having distributed energy storage systems along the grid can make a significant difference in maintaining service quality. For instance, during severe grid disruptions that could lead to major blackouts, having a storage system supporting a power plant can be crucial to quickly restarting electricity generation.

The storage type that has been favoured for many of these applications for years is electrochemical storage, also known as BESS, Battery Energy Storage Systems. It is a popular and widely used tool because of its ability to respond quickly and precisely to energy demands. In fact, some types can respond within milliseconds to grid demands, injecting or absorbing the required energy. Another advantage that BESS assure is that the batteries employed are reversible: they can both supply and absorb power. Their widespread use has also led to the creation of batteries of different shapes and sizes, suitable for a wide range of applications, and greatly reduced their cost. There are many types of energy storage, but for the purposes of this text we will focus mainly on electrochemical storage.

1.1 Architecture of an BESS

In order to design an ESS(Energy Storage System) correctly, it is necessary to be aware of the three main parts into which it is divided. An ESS must communicate with the rest of the grid, so it is essential to have a power conversion system between the storage units and the grid. Its role is to charge and discharge the storage technology in safe conditions. It is obvious that it will need some sort of storage system to preserve the energy and an energy management system to ensure optimal operation, other than safely controlling the temperatures. This simplifying division is embodied in figure 1.

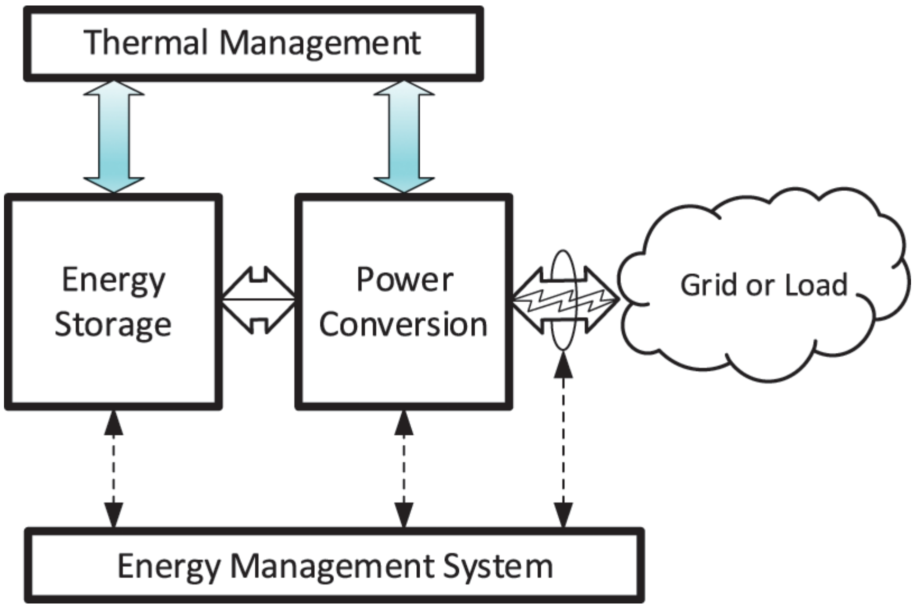

Figure 1: General structure of an energy storage system [1]

As clearly as it shows the protagonists of this structure, these systems need to be split in the single components in order to actually build a proper energy storage. Speaking specifically of a BESS, the physical parts that are crucial to its operation are.

- **Transformer:** A transformer is an electrical machine that operates on alternating current and is used to convert electrical power from one voltage level to another. During the transfer of power from the point of production to the point of use, losses inevitably occur. By using transformers at the ends of the transmission path, energy can be transported more efficiently by adjusting voltage parameters only near the point of use. In the present context, the transformer is located at the point of connection to the national grid. Its task is to raise the voltage when the battery energy storage system delivers energy to the grid, and lower it when the BESS absorbs energy from the grid, bringing it down to values that conform to the storage system.
- **Inverter:** Inverters are DC/AC Converters: they convert direct current to alternating current and viceversa. Batteries deliver DC current only, while the transmission grid is an AC. An inverter is a necessary link to allow energy exchanges between these two components. In addition, it is equipped with safety sensors and switches to prevent short circuits or overloads, protecting both the bess and the grid.

- **Batteries units:** They consist of electrochemical cells capable of storing chemical energy. Individually, the cells are not very powerful, but they are very versatile. They can have many shapes and technologies and are modularly configured to better represent the specifications of the case

These elements are represented in a simplified type configuration in the figure 2.

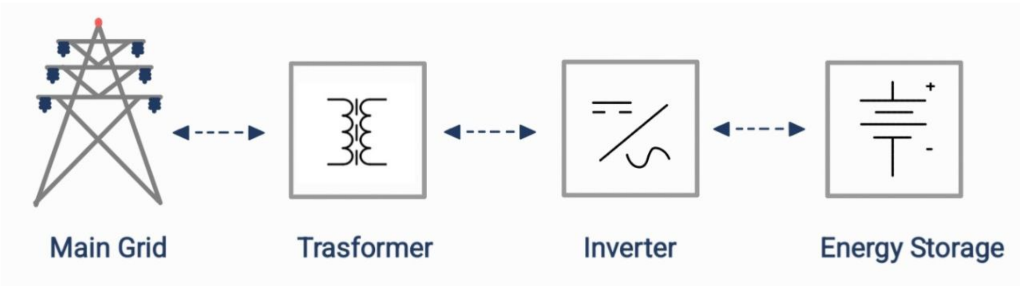

Figure 2: Fisical components

1.2 Electrochemical Storage

As foretold the main technology for ESS is electrochemical storage, or more commonly known *batteries*. Since for the nature of the battery energy storage system(BESS) it is essential for the electrochemical storage to be rechargeable, the batteries employed are only secondary batteries, otherwise known as rechargeable batteries. Reversible chemical reactions are used to store and release energy: during discharge, the negative electrode is oxidised, producing electrons, while the positive electrode is reduced, consuming electrons. These electrons flow through an external circuit creating a flow of electrons as it's depicted in figure 3. The flow of electrons produced inside the batteries is the electrical current.

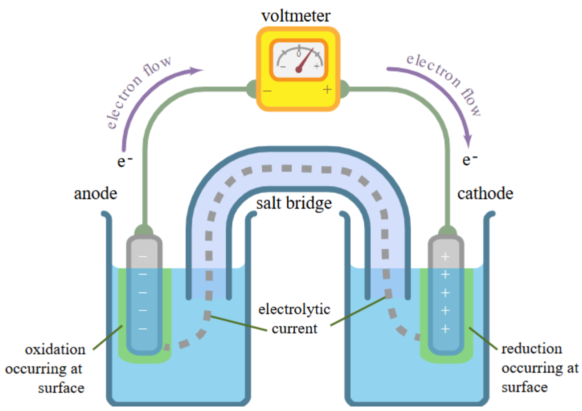

Figure 3: Electrochemical reaction inside the battery cell

Batteries have been extensively developed due to their numerous advantages. They are distinguished by a high energy density and a high efficiency of energy conversion and storage process. Since batteries come in various designs and sizes they have estensive experience in portable application and electronic vehicles. Electrochemical cells are scalable technologies, so their modular nature allows for power capacity to be increased or decreased by adding or removing battery units.

This technology still has limitations.Aside from being an expensive technology, batteries must be carefully sized to meet the specific needs of the application, making trade-offs between power and energy demand. The have a limited lifetime and some can be difficult to recycle. The exponential increase in the use of batteries has shown us the shortcomings in their regulation, causing problems with their disposal. Efforts are being made globally to remedy this with regulations such as the European Regulation (EU) 2023/1542 [16]. It is a document of more than one hundred pages that provides indications on the creation and disposal of batteries as well as methods to monitor them during its lifetime.

Electro chemical storage can be divided into several categories, distinguished by the specific chemical reactions that govern their operation, with each category being particularly well suited to certain fields of application. In order to provide a clearer perception of the magnitude of the values typically encountered, table 1 outlines the most relevant battery parameters together with the ranges in which they are commonly observed. "The quantities presented below are those considered in the table, as they summarize the key information that should be known about a battery before employing it.

- Anode : the battery's electrode where an oxidation reaction occurs (release of electrons). It is considered negative
- Cathode : the electrode an electrode where a reduction reaction occurs (gain of electrons). It is considered positive
- Cell voltage: both at open circuit and at operating value
- Efficiency: the efficiency of the storage process, comprehensive of charging and discharging process, also called Rount Trip Efficiency.
- Self Discharge Rate: proportion of stored energy lost by self-discharge over a time period
- Cycle lifetime: a measure of how many cycles a battery can deliver over its useful life

- Expected lifetime : the useful life of the battery if it is used following the nominal directions
- Specific Energy: the amount of energy a battery can store per unit mass, it indicates how much energy the battery can provide over time.
- Energy Density: similar as before it informs about the amount of energy stored per unit volume.
- Specific Power :the amount of power a battery can deliver per unit mass, it gives information on how quickly the battery can deliver energy.

	Lead–Acid	NaS	Li Ion	VRFB
Chemistry				
Anode	Pb	Na	C	$V2^{+} \rightleftarrows V3^{+}$
Cathode	PbO_2	S	$LiCoO_2$	$V4^{+} \rightleftarrows V5^{+}$
Cell Voltage				
Open circuit	2.1	2.1	4.1	1.2
Operating	2.0-1.8	2.0-1.8	4.0-3.0	
Specific Energy (Wh/kg)	10-35	133-202	150-200	20-30
Energy Density (Wh/L)	50-90	285-345	400	30
Specific Power (W/kg)	35-50	36-60	80-130	110
Efficiency (%)	70-90	70-90	85-98	60-85
Power Rating		MW scale	W to MW	100kW to 20MW
Self-Discharge Rate (%)	0.09-0.4	0.05-1	0.1-0.36	
Cycle life (cycles)	200-700	2,500-4,500	1000	12000
Expected Lifetime (years)	3-20	5-15	5-15	5-20
Advantages	Low cost, good reliability	Potential low cost High cycle life	High specific energy and energy density, low self discharge, long cycle life	High efficiency, indipendent energy and power sizing, low replacement cost
Limitations	Limited energy density, recycling programs, thermal managment	Thermal management, safety, small scalability	Safety costrains, recycling programs, costs	Cross mixing electrolytes, early stage of development

Table 1: Main characteristics taken from "Large Energy Storage Handbook"[17]

1.2.1 Lithium-ion batteries

Reading the table 1, lithium-ion galvanic cells have a graphite anode and a $LiCoO_2$ (lithium cobalt oxide) cathode. During charging and discharging, lithium ions move between these electrodes through the electrolyte solution, following this redox reaction

$$LiC_6 + CoO_2 \rightleftharpoons C_6 + LiCoO_2 \tag{1}$$

Lithium-ion technologies were developed with the aim of overcoming the high reactivity of lithium metal to water. In fact, the operating principle of lithium-ion cells is that of intercalation (and de-intercalation) of the ion within the materials that make up the two electrodes: it allows ions to diffuse within a host structure, without going to change its crystalline structure and chemical nature.
The charge life in lithium batteries is closely related to the amount of energy delivered and the material used, and the overall performance varies over time. Especially Lithium-ion secondary batteries (the reversible kind) experience performance degradation even when not in use. This phenomenon, known as *calendar aging*, occurs over time and significantly impacts the expected lifespan of the battery. Overmore usually batteries suffer from *cycle aging*: gradual performance degradation due to repeated charge and discharge cycles. Aging manifests itself as a decrease in power capacity and in an increase in the internal resistance of the battery. Once the battery's performance degrades to specified levels, it may be considered at the end of its usable life, with reduced efficiency and capacity that might no longer meet practical application requirements. It's necessary to comprehend and accurately forecast the lifespan of these batteries to optimize their performance, reduce expenses, and ensure the sustainability of energy storage systems: this can be obtained with mathematical estimations and models approaches [18].
Among the various types of lithium-ion batteries, the Lithium Nickel Manganese Cobalt Oxide (NMC) battery is also worth mentioning. The NCM technology, like other lithium-ion cells, has a graphite anode, while the cathode is made of a combination of nickel, cobalt, and manganese: these materials improve ions flow through a three-dimensional spinel structure, enhancing the thermal stability of the cell [17].

1.2.2 Other types of storage

In order to get a comprehensive view of energy storage systems (ESS), it is important to recognize that there are many other types of storage besides BESS. These solutions have been developed to address various specific problems and prove to be extremely useful. When designing a system interfaced with generating plants that needs to provide stability to the grid, BESSs are the most cost-effective solution, as explained above. However, the efficiency and versatility of these storage systems can be further improved when combined with other types of storage. In this section other types of storage are intended to be reported, starting with three technology belonging to the class of mechanical storage.

Mechanical storage comprehend storage systems where electrical energy is stored in the form of mechanical energy. These solutions are suitable when dealing with non-programmable renewable sources, because they allow the exploitation of moments of excessive production and stabilize the grid. They are especially recommended in the case of plants that are particularly isolated from the grid. Some practical examples are

- Hydroelectric Pumping (PHS): water is pumped into an elevated reservoir and released to generate electricity when needed.

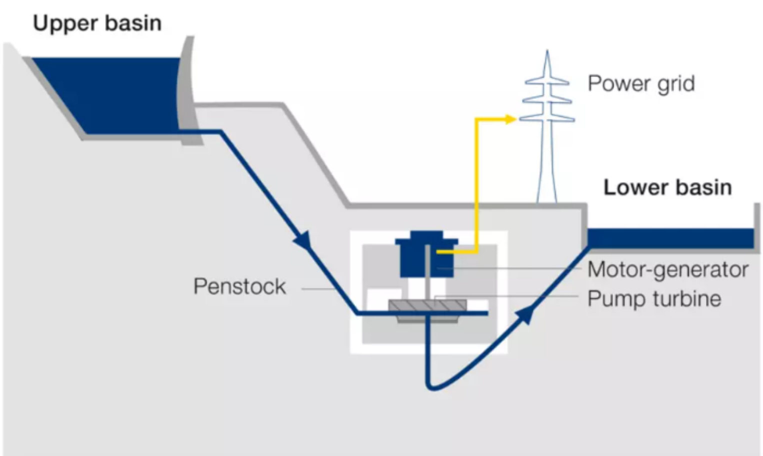

Figure 4: Structure PHS

- Compressed air storage (CAES): electricity is used to compress air in natural or man-made quarries. On demand, the air is released in order to spin a turbine, used as an alternator, to produce electricity.

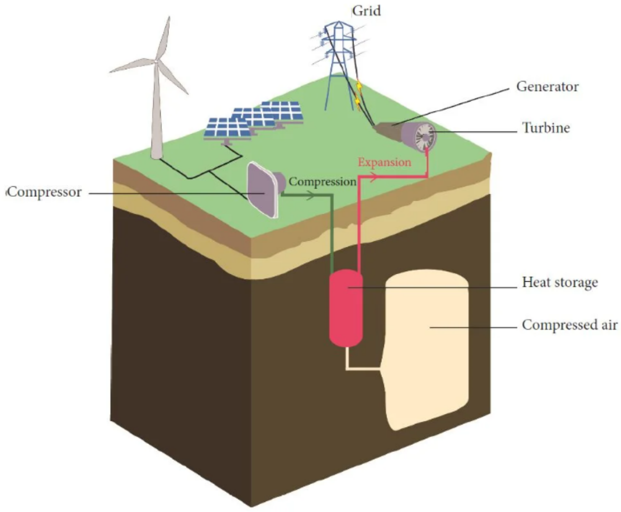

Figure 5: Structure CAES

- Flywheel Energy Storage (FES): Uses a flywheel rotating at high speed to store kinetic energy.

Another category of storage is purely electrical storage: these solutions store energy directly without intermediate conversions. They are preferred in contexts where rapid response and high efficiency are required but are not applicable for BESS since they are not suitable for storing large quantities for long periods of time. In this category can be found

- Superconducting Magnetic Energy Storage (SMES): devices capable of storing energy within a magnetic field generated by electric current flows

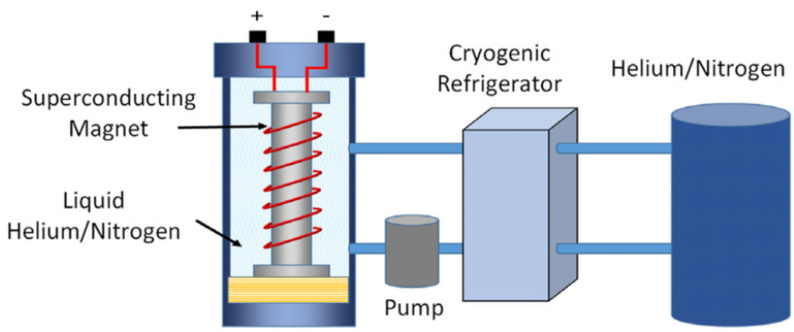

Figure 6: Schematic diagram of a SMES

- Supercapacitors : Capacitors store energy through the separation of electrical charges in an electric field, without involving chemical reactions as in batteries. Supercapacitors have a much greater storage capacity than traditional capacitors and can store energy or release it in a very short period of time

1.3 Transformer

The italian electrotechnical committee (CEI- Comitato Elettrotecnico Italiano) defines the transformer as

> “Una macchina statica con due o più avvolgimenti che, per induzione elettromagnetica, trasforma un sistema di tensione e corrente alternata in un altro sistema generalmente di differenti valori di tensione e corrente, alla stessa frequenza, allo scopo di trasmettere la potenza elettrica.”[19]

It essentially state that the trasformer is a static machine with two or more windings that, by induction electromagnetic induction, transforms one system of alternating voltage and current into another system generally of different values of voltage and current, at the same frequency. A simple diagram rappresenting a two windings trasformer is shown in figure 7.

In addition to the function of voltage lowering/raising, it can perform other important functions such as impedance matching and providing measurements. One of the most advantageous aspects is that it provides galvanic isolation between the grid and the storage system.

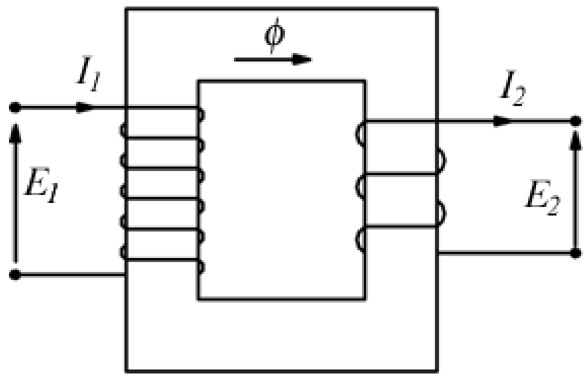

Figure 7: Simplified diagram of a transformer

The machine is based on the law of induction (Faraday’s, Neumann’s, Lenz’s law): an alternating current (AC) passing through the primary winding generates a variable magnetic field inducing a voltage in the secondary winding. This transfer of energy occurs without direct contact.The risk that in the event of short circuits or faults the high current may ruin components, foul waveforms, or cause personal injury is reduced.

1.4 Power Conversion System

Usually employing one or more converters the role of the PCS is to convert the electricity provided by the storage system into a grid-compatible quantity. Its objective it's to regulate and control the amount of energy released, matching it to the needs of the grid and improving the stability of the electrical system. So far we have been talking about the grid, but BESS have many applications: they can be programmed to interact within microgrids, with simple loads or generation units. Having an internal conversion system within the BESS allows versatility of use as required.
The structure of the PCS depends on the application for which the BESS is intended, but it must also allow for optimal storage system operation.You want to distribute the use of the components evenly to avoid overheating.Especially in the case of batteries, if one unit were to overheat it would drastically reduce its life and worsen the efficiency of the whole system. A general diagram summarizing the recommended control structures and strategies for BESS systems is shown in figure 8.

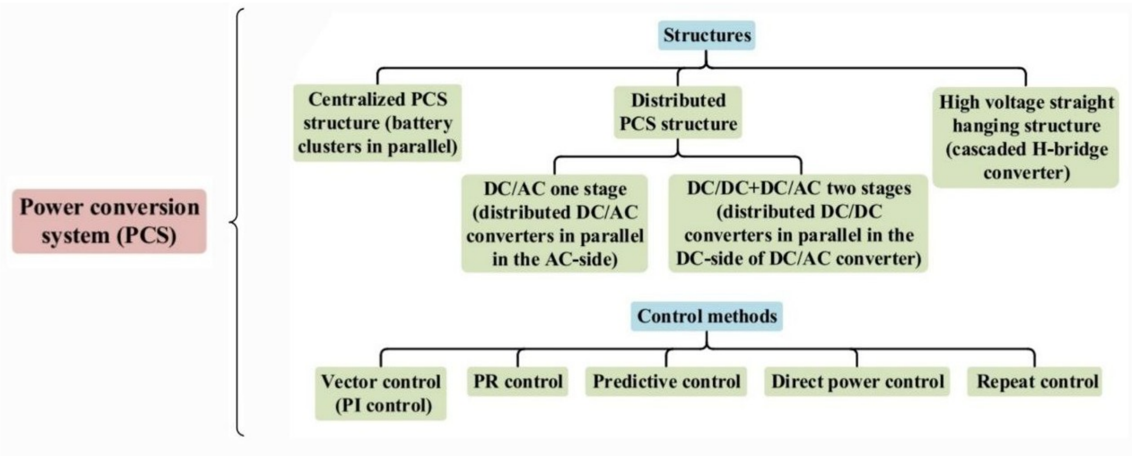

Figure 8: Summary outline for PCS control structures and strategies [2]

1.5 Battery Management System

In section 1.1, the basic practical elements for operation were mentioned but an equally important component was left out: the Battery Managment System(BMS). It is a crucial component for a BESS because its main function is to process the signals and information coming from the battery system to ensure optimal and safe operation. While components such as the interver or transformer directly act on the energy in transit, the BMS deals more with information and communication. It

can have a simple or more advanced design, but its primary function is to prevent harmful operations to the storage system. It can often be supported by a supervisory system control (SSC), which in addition to keeping track of the status of the storage system is responsible for keeping the system in its entirety under control.
BMS tasks may include

- Real-time monitoring:includes sensors that monitor the output voltage and current, as well as the internal temperature of the storage unit
- SOC (State Of Charge): it represents the amount of energy stored in the battery relative to its maximum capacity
- SOH (State Of Health): it measures the condition of the battery over time, assessing the degradation and remaining capacity compared to the initial capacity
- Capability estimation: it means the safe management of charge and discharge process. It must avoid extreme charge/discharge profiles, overcharging or undercharging that could easily degrade a storage unit.
- Remaining time and available energy
- Emergency protocols: especially in large-scale BESS installations, the BMS typically includes all safety measures, such as fuses and circuit breakers, housed in a low-voltage panel, which ensure the batteries remain safe in case of a fault detected by the real-time monitoring.

All definition are extracted from "Large Energy Storage Systems Handbook" by Barns and Levine [17].

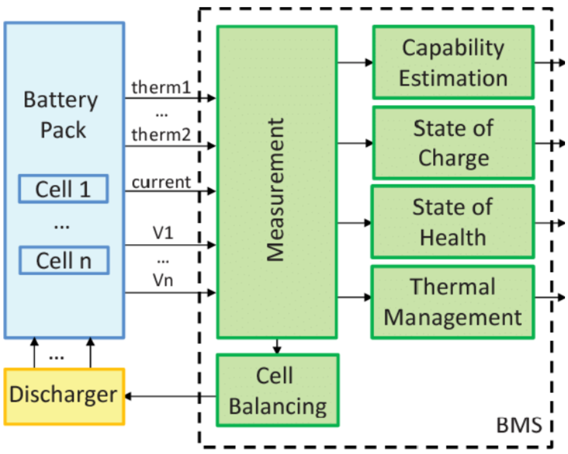

Figure 9: Block diagram of a BMS[3]

1.5.1 Auxiliaries

Auxiliary systems range from the most mundane, such as heat management and air conditioning, to more specific additions, such as accurate future performance prediction systems. These additional systems depend on the customer's requirements and can be added to the BMS. Looking at the basic requirements, a medium-sized BESS facility will need its own lighting system and a range of emergency measures, such as fire-fighting systems.
Above all, it is important to have thermal management system. Battery systems generate heat, as every component experiences losses mainly in the form of heat. Allowing batteries to overheat can shorten their life, cause permanent damage and increase the risk of fire. The aim of thermal management is firstly to keep the cell temperature within the correct power range and secondly to maintain a uniform temperature throughout the system. Optimum performance levels are specified by the manufacturer, but typically for lithium-ion cells are 20° C to 30° C for Li-Ion(Lithium-Ion battery) and 18° C to 28° C for NMC(Lithium Nickel Manganese Cobalt battery) [20]. Be aware that even at lower temperatures the battery may suffer, as this can affect its capacity and responsiveness. The air conditioning will need to be on all year round.

1.6 BESS Application

During recent years, BESSs have become widely used, expanding their types and applications. This thesis work arises by exploring some of these applications in support of thermal power plants. However, before we move on to this area of expertise, it is vital to briefly outline the most renowned and frequently cited applications of battery energy storage and to consider the significant potential they have for the future. This will help us to fully understand the importance of this specific role. Note that each application must come with opportune management changes and plant structure suited to the case.

Taking reference from the figure 10, the applications can be classified according to the system with which the storage interacts: either in support of a production plant, in support of the grid, or directly with the loads. This classification has been adopted as the framework for presenting the different BESS applications.

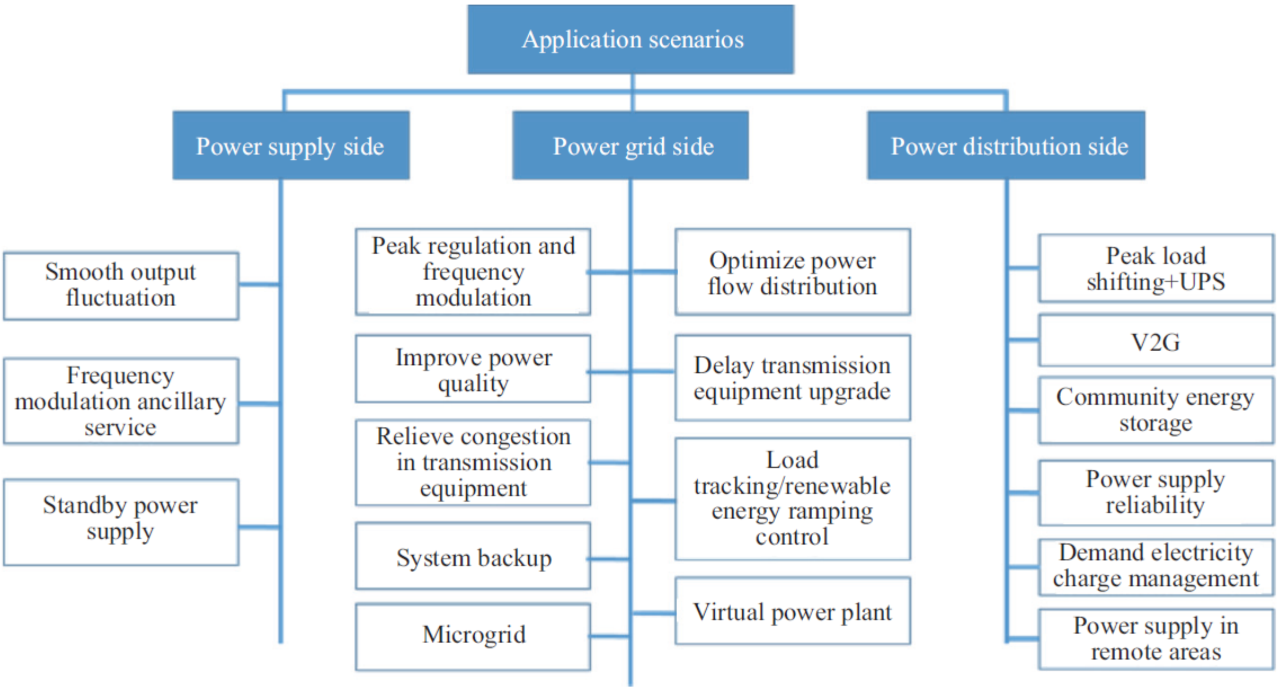

Figure 10: Figure taken from the article of Li X. and Wang S., 2021[4]

BESS in support of a production plant When we talk about BESSs in support of a production plant, it is important to clarify the type of production units involved, as the role of the BESS can vary significantly.

If the BESS is interacting with *renewable production units* the storage plant assumes the role of compensating for the natural variability and intermittency of renewable sources such as solar and wind power. Since these energy sources cannot be directly controlled by human intervention, their output inevitably fluctuates with weather conditions and time of day. The function of the BESS is therefore to smooth out these fluctuations with stored energy in order to maintain a more stable and predictable supply of electricity,improving the reliability and overall efficiency of renewable integration within the energy system and ensuring that the renewable unit remains consistent with the demand requirements of the grid or the connected loads. Studying the graph in figure 11 taken from an experimental study published by IEEE[21] it's clear how the addition of a BESS significantly reduces fluctuations in the energy available for use.

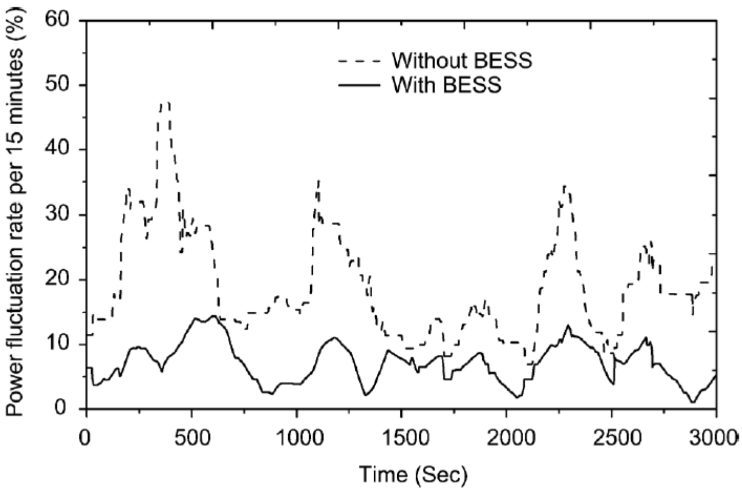

Figure 11: Power fluctuation rate profiles

The other possibility is to refer a BESS in support of *traditional production units*, such as thermal power plants. In this case, the greatest support a BESS can provide is frequency and voltage regulation support.
The power grid must maintain a constant balance between power generated and power consumed, to avoid serious grid imbalances that can bring great inconvenience to people and service quality. Under nominal conditions of operations the grid frequency in Europe should be 50 *Hz* while in case of discrepancies between supply and demand there are frequency transients that can severely damage components. Simplifying, there are two possible scenarios

- Under-frequency transient: in case of overload, the energy supply is less than the demand. Given the discrepancy the grid absorbs more energy and this causes voltage sags as well as sags in the grid frequency.

- Over-frequency transient: in case of underload, the energy supply is higher than the demand. Feeding more energy into the grid causes increase in both the frequency of the wave and its voltage.

Referring to figure 12, the areas of regulation up correspond to an under-frequency transient, where the frequency needs to be increased, while the areas of regulation down correspond to an over-frequency transient, where the frequency is already high and needs to be reduced.

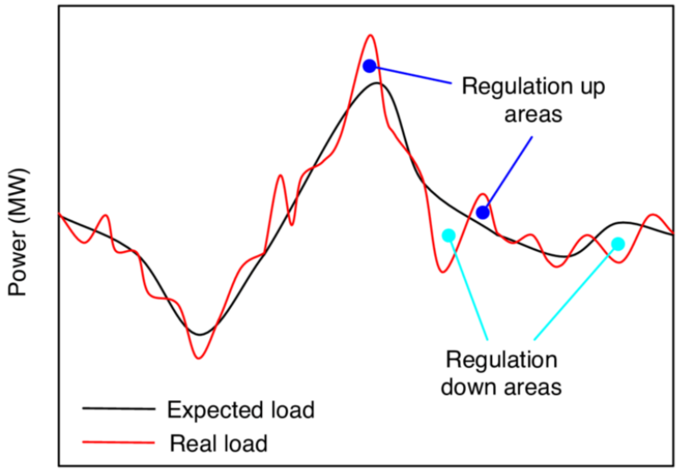

Figure 12: Simplified example of frequency regulation [5]

In both cases BESSs can be of great help. In the case of overload, missing energy can be drawn from battery storage, while in the case of underload, the BESS can absorb the surplus energy. The details on what exactly frequency regulation comprehend will be discussed in the section 1.6.1, but it is important to note that in case the BESS is to be used for frequency regulation or voltage regulation careful battery management must be done: they must always have enough space available to provide these adjustments, both to erogate power or to store it. This role was formerly entrusted to the production units themselves, which for the same reason were forced to work within certain power margins other than their actual production maximums and minimums: they needed room for adjustment. BESS have proven themselves more accurate and faster in this function, and it is possible to free thermal power plants from the former limits on production.

Not to forget the Black Start function, also called standby power supply. In case of emergency, conventional power plants need a lot of time and energy to restart and become operational again. Consider the figure 13 showing the trend in power production in Spain after the blackout on 28/04/25: although the interruption in production was extremely rapid, it took many hours to restart the production units. This deficit could be aid by installing emergency start-up back-ups that would respond much faster.

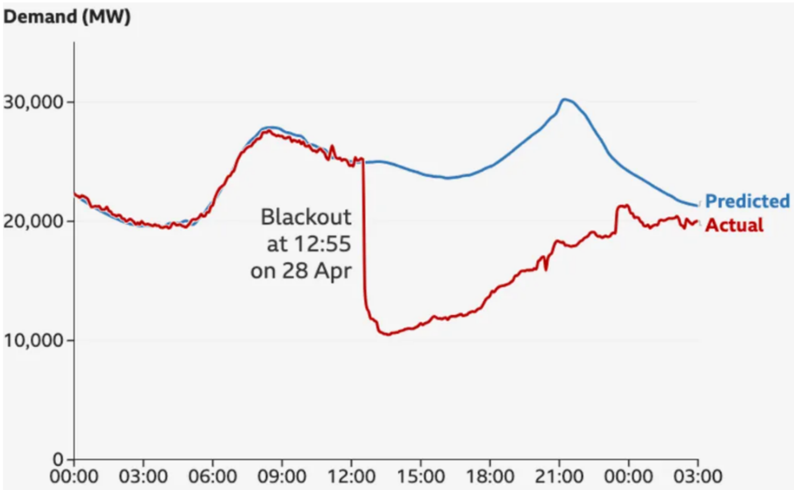

Figure 13: Actual power demand after the black out from the Red Eléctrica de España

BESS in support of the grid Versatility of storage systems gives its best in support of grid applications. Facing the evolution of the grid toward bidirectional power distribution energy storage is one of the keys to ensuring flexibility, security and reliability to the grid. They are expected to support distributed power generation and practice multifunctional coordination. Technologies and especially management strategies are evolving in that direction, but so far only a few applications have proven clear and functional.

Some strategies follow a load-leveling tecnique. As was expressed in the previous paragraph, it is important that there is a balance between the power produced and the power demanded. It is possible for power demand to vary unexpectedly over time. One can exploit BESS as elements of flexibility to give support during these sudden changes. A common strategy is the "peak shaving service" : this service consists of absorbing excess electricity during periods of high production and subsequently releasing the stored energy when production is lower or when electricity prices are less favorable. In other words, the BESS acts as a buffer that shifts the availability of energy from moments of surplus to moments of greater demand or economic value.Through this mechanism, peak shaving mitigates sudden peaks in the load profile by flattening the demand curve during the day, as can be seen in figure 14 . This not only reduces stress on the grid and generation assets but also improves overall system efficiency and reliability.

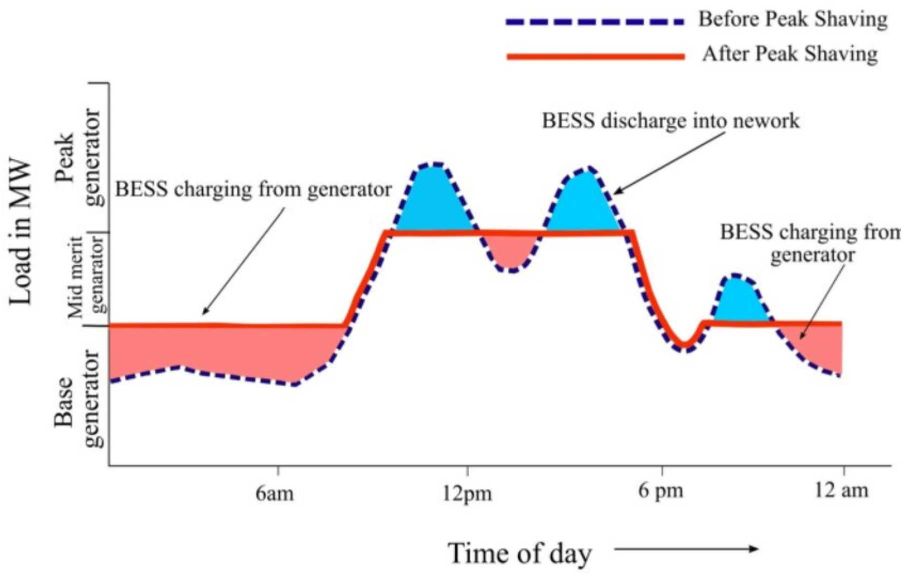

Figure 14: Example of peak shaving using a BESS [6]

Furthermore, having strategically placed storage systems can be a game changer in solving some grid transmission and congestion issues. When power demand is not supported by actual transmission capacity, distributed storage can relieve congestion without incurring the onerous congestion-related costs and charges. Or in case of strong power quality problems, such as voltage dips or excessive harmonics, one can also choose to supply directly from storage systems instead of the grid to avoid fewer problems for utility users. Of course, these operations are possible only under approval of the TSO(transmission system operator), in Italy represented by TERNA. The idea is that stored energy can be exploited along the distribution to meet the demand without aggravating the grid and improving the power quality.

BESS in support of the distribution side Regarding energy storage in relation to end users, the various applications focus on saving electricity cost for users. There are already a number of regulated solutions that can not only save money but turn storage facilities into an additional revenue opportunity: self-consumption and electric communities to name a few.The important thing is to empower the end user in how themselves can manage his or her energy and his or her revenue opportunities.For some endusers, direct distribution can be difficult so for customers in remote areas installing an emergency BESS can be a way to secure electricity.
It is worth mentioning the importance that BESS could have within the growing

world of Vehicle to Grid(V2G). The ability to charge and discharge electrical vehicles(EVs) into the distribution grid and the influence of this process on grid operational security cannot be underestimated because the large-scale access of EVs will affect power system planning and operation. The future idea is to manage the EV charging and discharging process in a scientific and orderly manner using distributed and interconnected storage systems.

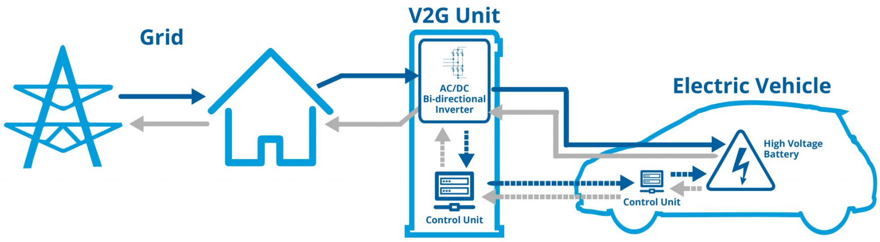

Figure 15: Fundamental elements for the functioning of Vehicle-to-Grid technology

1.6.1 Frequency regulation

Frequency regulation plays an important role for the purpose of this thesis so it will be explored in detail in the current section.
The changes that have taken place in the electricity sector in recent years have made the security status of the electricity system critical. With the term security we refer to the reliability and resilience of the distribution system on the ground. With the energy transition, there is a strong focus on replacing traditional energy sources with non-programmable energy sources even if this leads to a decrease in frequency and voltage regulating power. In fact, the different frequency regulations are among the ancillary services required by TERNA from generation plants. In order to safely manage the electric system and ensure, at the same time, an adequate level of service quality a process has been initiated to gradually open the services market to new types of resources. Given their speed of response, accuracy, and functional flexibility BESSs are among the first resources to be incorporated.

Frequency regulation is a service mandated by the national Transmission System Operator (TSO), and as such, it is subject to strict oversight and regulation. To be eligible to provide frequency regulation, a generating unit must meet specific technical criteria. There are three basic types of regulation with different requirements and objectives, which timing response is shown in figure 16.

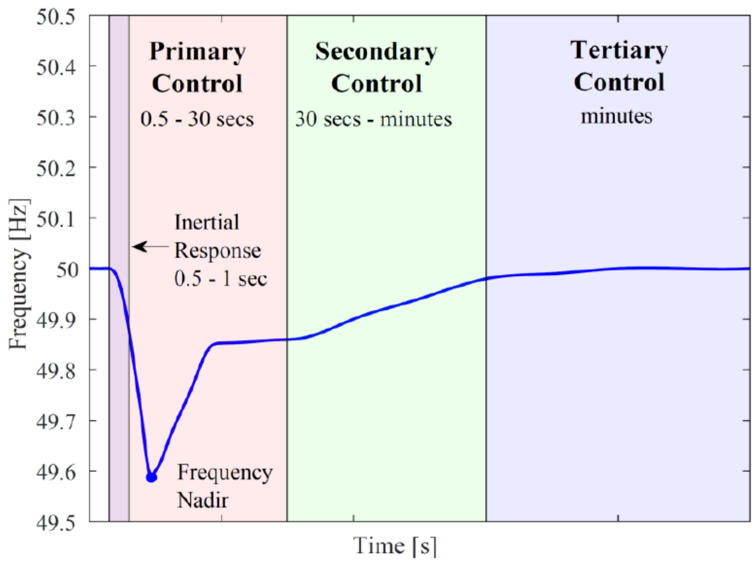

Figure 16: Figure taken from MDPI article from 2020[7]

- **Primary Frequency Regulation (PFR)**
  According to TERNA's documents, PFR is defined as the set of operations aiming to maintain the balance between generation and demand in an electric system. The band of energy that is delivered or absorbed to correct the imbalance is from a reserve called "Primary Regulation Band" [8]. Primary regulation service is **compulsory** for all relevant generating units with efficient power output above 10 MW. Relevant generating units (Unità Produttive Rilevanti-UPR from now on) feature both generation plants and generation plants in cooperation with storage units, excepted renewable production power plants, as they are not suitable for providing these services.

  UPR with regulatory function are required to

  - assure an active power reserve of not less than 1.5% percent of the declared efficient power at the registry of production units(RPU)
  - to have speed measurement accuracy of 0.02% under any operating condition
  - respond within 15 seconds of the start of the disturbance with at least half of the required power and within 30 seconds with the full required power.
  - to stably deliver the new value of requested power for at least 15 minutes after the start of the frequency imbalance

The first criteria implied that the power unit must not work between its maximum and minimum values but between the maximum considering the needed regulation band. This concept, already previously announced, is illustrated in the figure 17

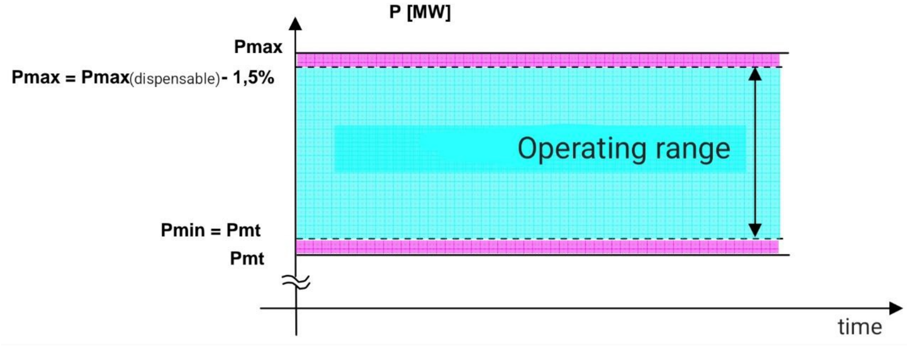

Figure 17: Operating range for a production unit on the continent [8]

- **Secondary Frequency Regulation (SFR)**
  The SFR, or frequency-power regulation, is a regulation service created to re-establish the nominal frequency value and programmed exchange power values. It works in response to the grid controller signals to return to the nominal frequency as quickly as possible and avoid trasmission problems. It can react more slowly than the PFR and is an exemption service from the TSO: if activated from TERNA it can be remunerated. SFR, too, acts on a margin of dedicated power, called "secondary reserve" but the value of exchange power can have a wide margin depending on operating conditions.The required secondary reserve must be able to be delivered continuously for at least 2 hours.

- **Tertiary Frequency Regulation (TFR)**
  In the case of prolonged use of the secondary regulation band, the TSO can restore a portion of the power margin allocated to this regulation by using additional available power called Tertiary Regulation Reserve. Its objective is always to restore balance in the grid and stabilize the frequency but unlike the previous ones it is carried out at the request of TERNA, which issues operating provisions (such as bringing reserve UPs into service or changing the power produced by UPs already in service). Primary, secondary and reserve margin adjustments are the only adjustments allowed in normal continuous operation of generating units. Any additional power and speed adjustments must be agreed upon and will be treated by TERNA as a request for deviation.

Another factor that influences the stability of the electrical system, and consequently frequency stability, is the reduction in the inertial response of the electrical system. Inertia measures the system's ability to "withstand" an abrupt imbalance between generation and system load without excessive changes in grid frequency. The gradual reduction in system inertia, due to fewer synchronous machines being dispatched, results in exacerbation of frequency variations following events, which must be contained within extremely fast response times that are not always compatible with the current contribution of primary regulation. This disruption could lead to the rise of dynamic, oscillatory and aperiodic behaviors, which are dangerous for the network.[22]
In addition to the frequncy adjustments already presented above, it is essential to provide new network services to handle the consequences of the decreasing inertia of the grid. To counteract the effects on frequency stability, it is necessary to introduce a service characterized by a full activation time shorter than that of the primary regulation. Looking at the figure 16 this service will have to act in the unmarked space between 0.5 and 1 second. Such a regulation service is called *"Fast Reserve"* or ultra-fast frequency regulation.
It is not intended as a substitute for primary regulation but as a coordinated service with it to contribute to system safety. It will help improve the dynamic response of the first instants during frequency transients.

Fast Reserve The FR service is to provide a continuous and automatic response in active power, proportional to the frequency error, within 1 second of the event that triggered the service and with a response start-up time within 300 milliseconds. The required power profile is shown in the figure 18. The required power must be maintained for at least 30 seconds and then perform a linear de-ramp in 5 minutes until the activated contribution is cancelled.

Modulation of active power coming from the Fast Reserve Unit(FRU) occurs in two ways: according to the Δf-ΔP characteristic curve or according to activation driven by starting setpoint sent by Terna.
The qualified power of a FRU must be between 5 MW and 25 MW. These values were chosen so that the unit can provide meaningful support but still allow for greater distribution of service on the grid. It is preferred not to use a single storage for grid FR for reasons of safety and convenience. The maximum quantity for which bids may be submitted by each bidder may not exceed 75 % of the quantity to be procured from the same area, so as to spread the load. This is a service paid for by TERNA according to a well-established schedule of hours and days. The plant may also choose to offer other hourly slots for FR regulation for additional profit,but they require TSO approval.

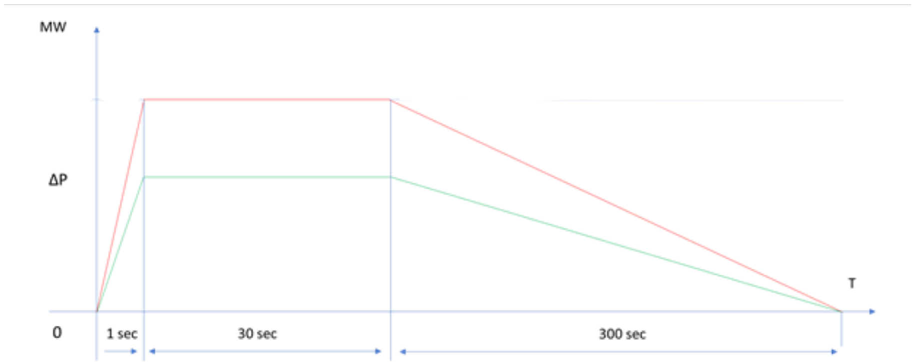

Figure 18: Dynamic of the Fast Reserve service

Furhtermore fast reserve unite devices under all operating conditions must be able to remain in parallel with the grid for voltage values expressed by the equation 2

$$0.85\,V_n \leq V \leq 1.15\,V_n \tag{2}$$

1.6.2 Terms of remuneration for ancillary services

There are numerous small gaps in the electrical system that can be alleviated or resolved thanks to storage systems.It is up to national organizations to understand how to allocate these resources appropriately, including from a regulatory and economic perspective.So far, this text listed the regulatory characteristics necessary to qualify a technology for fast reserve services. Now it will illustrate the economic paradigms used to bring these technologies to market. One example is the Both the UPI Pilor Project, proposed by TERNA, which led to the construction of the two BESS plants explored in the next section. The UPI pilot project for fast reserve was conceived as a first step to integrate electrochemical storage systems in support of fast reserve services within the Italian market. It was used a pilot to shed some light on how to introduce batteries and their economic remuneration into the framework of ancillary service provision.

Figure 19: Italian company responsible of electricity transmission networks

A sales system based on long-term auctions, generally lasting five years, was chosen. The goal was to encourage investment in new technologies and guarantee them a place in the market. Terna made a certain number of hours and annual energy volumes available, which could be auctioned to a limited number of participants that met the requirements set out in the project's tender and the characteristics of the fast reserve. An example of the available slots can be seen in the figure 20, extracted from the documents provided for the 2024 auction. After the auction, the winning bidder received a fixed fee for the availability of the contracted capacity, regardless of the contingent conditions of the electricity system.

ore/mesi	Gennaio	Febbraio	Marzo	Aprile	Maggio	Giugno	Luglio	Agosto	Settembre	Ottobre	Novembre	Dicembre	Totale
0	2	0	0	0	0	0	0	0	0	0	0	2	4
1	9	0	0	0	4	0	0	0	0	0	0	6	19
2	10	1	0	6	8	0	0	1	0	0	0	9	35
3	10	1	1	6	8	1	0	1	0	0	0	9	37
4	10	1	2	6	8	1	0	1	0	0	0	9	38
5	6	1	2	6	8	3	0	1	0	0	0	7	34
6	3	0	2	6	5	3	0	4	0	0	0	3	26
7	2	0	2	6	9	6	0	7	0	0	0	2	34
8	2	0	2	6	9	7	0	7	0	0	0	2	35
9	2	0	5	11	9	8	0	13	5	0	0	2	55
10	2	0	10	11	9	9	1	17	7	4	0	2	72
11	3	3	10	11	9	10	1	18	9	6	0	2	82
12	3	4	10	11	9	10	6	19	9	7	0	2	90
13	3	4	10	11	9	10	7	19	9	7	0	2	91
14	2	4	10	11	9	10	7	19	9	7	0	2	90
15	2	1	10	11	9	10	7	18	9	7	0	2	86
16	2	0	9	11	9	10	3	11	8	5	0	2	70
17	0	0	4	10	9	8	0	10	3	0	0	0	44
18	0	0	1	10	9	5	0	6	0	0	0	0	31
19	0	0	1	9	9	0	0	3	0	0	0	0	22
20	0	0	1	1	0	0	0	3	0	0	0	0	5
21	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
Totale	**73**	**20**	**92**	**160**	**158**	**111**	**32**	**178**	**68**	**43**	**0**	**65**	**1000**

Nota: l'ora indicata (es. 00:00) indica l'inizio dell'Ora di Disponibilità oggetto del servizio

Figure 20: Indicative estimate of Fast Reserve availability hours for the year 2024 [9]

The project officially ended in 2024. From 1 January 2025, Arera introduced a new sales paradigm called TIDE (*Testo Integrato per il Dispacciamento Elettrico* [23]) that will be implemented by Terna. Fast reserve and other ancillary services are now procured through short-term periodic auctions, held daily and weekly. This new framework allows for closer alignment with market needs, as both operators and customers can submit offers and requests directly to the market.
Remuneration will follow two methods:

- Capacity payment: the operator is remunerated for the availability of a certain power capacity, regardless of whether it is actually used. It is paid in €/MW and serves to ensure that resources are always available
- Service activation: the operator receives an additional payment if the service is actually activated by Terna following the detection of a problem. In this case, the payments are for the energy actually supplied, measured in €/MWh.

Compared to the pilot project model, the spot market introduces a more dynamic and competitive approach, marking the shift from a market focused on introducing and evaluating technologies to a system designed to promote their integration, privileging local efficiency and ongoing competition. It is enough to consider that, under the five-year auction model, if an operator was not admitted to the initial auction or did not win hours, they were excluded from the market for years. With this new solution, greater transparency, competition, and flexibility are achieved.

These are only some of the changes implemented with the reform of electricity dispatching in Italy starting in 2025. The document aims to put concentrated and distributed energy resources on an equal footing, ensuring that the best ones are selected at all times and for every specific need. In practice, TIDE aims to facilitate the full integration of clean sources and promote the use of efficient plants with advanced technologies.
The modified electricity context favors rapid and continuous evolution of the electricity supply mix, diversifying sources and technologies in order to improve the resilience and sustainability of the entire electricity system. This complexity of this plan is better explained by "The energy trilemma", the strategic challenge of simultaneously achieving three core objectives of energy policy: energy security, energy equity, and environmental sustainability. This concept is reported in figure 21.
The approach intended with the TIDE document is planned to be successful because it allows all three sides of the energy trilemma to be considered and studied simultaneously: by strengthening system resilience, they address security of supply; by fostering clean and efficient resources, they contribute to environmental sustainability; and by introducing more competitive, short-term mechanisms, they enhance affordability for consumers.

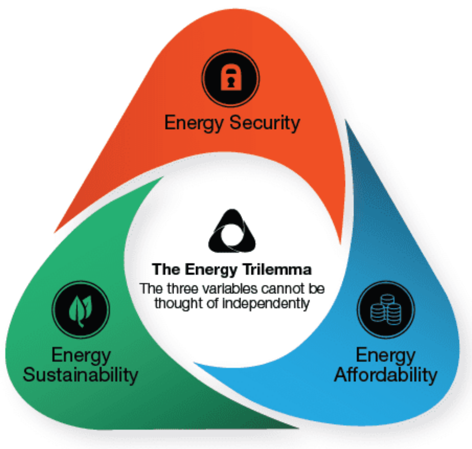

Figure 21: Indicative representation of the energy trilemma

2 Real-life case studies

In the first chapter, Battery Energy Storage Systems were introduced, emphasizing the variety of types and applications that have fostered their widespread use. In this chapter, however, the focus is on two concrete cases of integration of BESS systems to support thermal power plants.
As described in section 1.6, the benefits of integrating a battery system into an existing plant can be manifold, representing one of the new frontiers of innovation in which Iren S.p.A., one of Italy's leading multi-utilities in the energy sector, has chosen to invest. Two real-life examples of BESS plants built by Iren S.p.A. are here presented: one of 10 MW installed at the Moncalieri thermoelectric power plant and one of 16 MW at the Turbigo power plant. Both projects were developed in collaboration with Terna as part of the UPI Pilot Project [24].All design choices were made in fulfillment of TERNA criteria and in compliance with CEI-EN, IEC standards for the construction of electrical installations. This project is part of the initiatives aimed at distributing some of the network services across the territory. In particular, both power plants are being asked to support frequency regulation and potential fast reserve service.

2.1 Moncalieri

The Moncalieri thermoelectric power plant is one of the most important power and thermal power plants in Piedmont. Located near Turin, the plant features, in a cogeneration setup,the *3° Combined Cycle Thermoelectric Group* (3°GT) with thermal power output 328 MW and the *RPW 2° Combined Cycle Thermoelectric Group*(RPW 2°GT)with thermal power output of 345 MW .

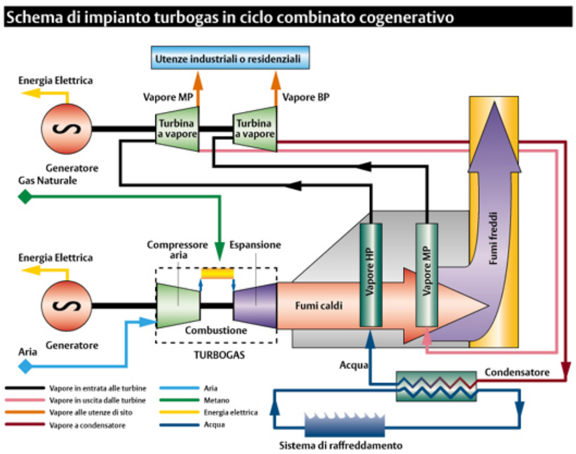

Figure 22: General scheme of a cogeneration combined cycle plant[10]

A “combined-cycle plant” generates electricity by combining two distinct cycles: in the first cycle, power is produced through the combustion of natural gas(gas cycle) ; the heat contained in the exhaust gases from the gas turbine is recovered and used to produce steam that drives a second, conventional turbine (steam cycle). The term ”cogeneration”, on the other hand, refers to the combined production of electricity and thermal energy.
It is an example of energy efficiency and environmental sustainability, contributing significantly to clean energy production and improved air quality in the region. If the turbines operate in purely electric set-up they would have an efficiency of 56-60%, but in cogeneration set-up they reach an efficiency of 85-90% each. The general scheme followed by the power station is indicated in figure 22.

Since it is a cogeneration plant,in addition to producing electricity fed into the national grid, the two groups also produce heat for the district heating network that begins at the Moncalieri power plant and reaches part of the municipalities of Moncalieri,Nichelino, Grugliasco, Collegno as well as much of the southern, central and northern areas of Turin. With a transmission and distribution network extending up to 769 km, this power plant is one of the largest plants in Italy (figure 23).

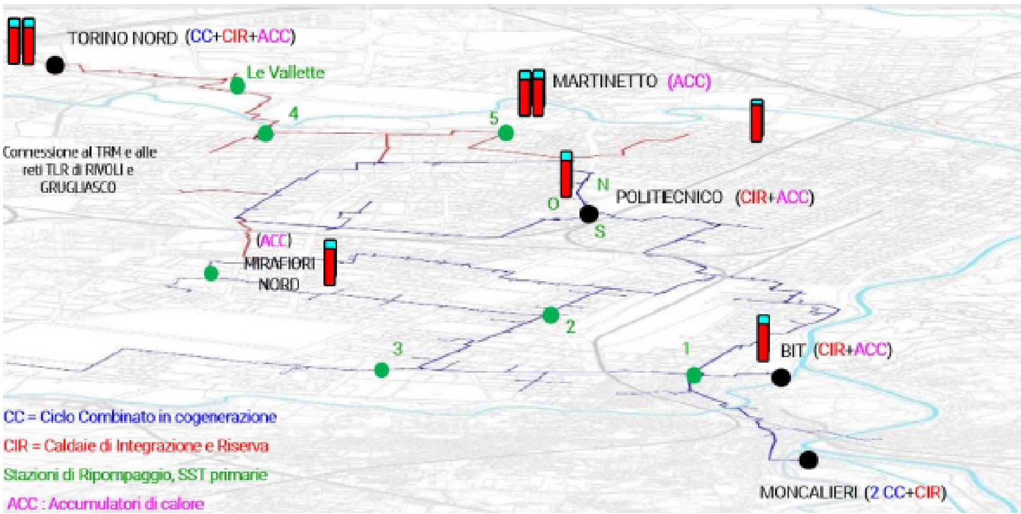

Figure 23: Geographical extent of the Moncalieri network [10]

Given the great importance of the plant, we are not surprised to learn that the plant has three integration and reserve boilers , named C1, C2 and C3, with a total thermal power of 150 MW, which are used to ensure the continuity of thermal power generation. By the same reasoning the plant also includes a electrical storage unit, which we will elaborate on in the following section 2.1.1

2.1.1 Layout of the installed batteries

The BESS installed at the Moncalieri power plant had to meet all the technical requirements of the Fast Reserve service and the Primary and Secondary Frequency Regulation service as outlined in section 1.6.1 following TERNA's official documentation and the grid code. For example, considering the declared power and the cogeneration efficiency mentioned above(sec. 2.1), the minimum installable power must satisfy the following equation:

$$P_{\mathrm{min}} = 1{,}5\% \cdot P \cdot \eta \tag{3}$$

Substituting the values

$$P_{min} = 1{,}5\% \cdot 673 \cdot 85\% = 8{,}6MW \tag{4}$$

An excess value was chosen for the design. After complying with all the norms, the characteristics required by the storage are collected in the table 2

	Value	Unit of Measure (UoM)
Required power	> 9	MW
Requided energy	> 7	MWh
Deliverable energy at EoL 10y	> 4.2	MWh
Design life	10	year
Round trip efficiency	> 90	%
Inverter efficiency	> 98	%
MT/BT transformer efficiency	> 98	%

Table 2: Minimum performance to be guaranteed [25] EoL = End of Life)

To meet these conditions, containers were commissioned and subsequently installed, divided for batteries, PCS groups and MT/BT power transformers. Given the available space, it was decided to position the BESS system outside, separate from the rest of the plant. The containers are made with self-supporting structure that can provide thermal and acoustic insulation as well as suitable cable segregations. Also they were already equipped with a forced air conditioning system and a fire protection system to keep the system safe and ensure optimal operation.

	20’	40’	UoM
Length	6058	12192	mm
Width	2438	2438	mm
Height	2896	2896	mm

Table 3: Standard dimensions for a 40’ container

The battery container is a standard ISO container 40’, with dimensions listed in table 3. For such large systems, it is not possible to design accurately or safely by considering only cellS: modular configurations of modules and racks must be considered. The chosen batteries are organized as follows:

- The single cell is the ”JP3 cell”. It’s a NMC lithium-ion battery cell, which technical performance is listed in the table 4. This specific type of tech has been discussed in section 1.2.1, so it will not be revisited here.

	Value	UoM
Nominal Capacity (0.3C)	64.0 ± 2.5%	Ah
Nominal Voltage (0.3C)	3.68	V
Voltage Range (Designed)	3.0 ∼ 4.2	V
Voltage Range (Usable)	3.0 ∼ 4.15	V
Nominal Energy (0.3C)	235.5	Wh
Weight	1,170	g
Operating temperature	5 ∼ 40	° C
Recommended operating temperature	23 ± 4	° C

Table 4: Nominal Specification of the JP3 cell [26]

- 2 parallel groups, each consisting of 14 cells in series, form a pack with a capacity of 128Ah and a voltage of a 51.52 V
- 17 packs in series are contained in a rack, corresponding to an energy of 112.098 kWh per rack and a voltage of 875.84 V
- By using 78 racks we arrive at the specifications in table 5, where the capacity is obtained as the rack capacity times the number of racks in parallel while the rated voltage remains the rack voltage.

	Value	UoM
Rack in parallel	78	
Nominal Capacity	9984	Ah
Nominal Voltage	875,84	V
Voltage Range		
upper limit	987,7	V
lower limit	714	V
Nominal Energy	8856494,08	Wh
	8,85649408	MWh

Table 5: Obtained Specifications

The battery units are evenly distributed across 3 separate containers to operate with more manageable current levels and to enhance reliability in the event of a failure.The final installed values are state in table 6. Each container is designed to be completely independent from the others and contributes approximately 33% of the total rated power, each with the necessary connections to interface with the PCS and the control and communication systems.

	Values	UoM
N° Containers	3	
N° Rack per container	26	
Nominal Capacity	3328	Ah
Nominal Voltage	875,84	V
Nominal Power	3.3	MW
Voltage Range Usable		
Upper limit	987,7	V
Lower limit	714	V
Nominal Energy	2,91	MWh
Total Installed Energy	8,74	MWh
Total Installed Power	10	MW
DC/AC efficiency including transformer	97	%
Expected Lifetime	10	year
Deliverable energy at EoL	6.57	MWh

Table 6: Parameters per container

Within each battery container, the racks are arranged into two parallel strings of 13 racks each. These are connected to two appropriately sized inverters, as illustrated in figure 24 : Q-Sn denotes the electrical panel relating to that subsystem. A redundancy strategy is employed to ensure power continuity even in case of a component failure. The final configuration meets system requirements and allows for continued operation at 70 % capacity even if one of the three sections is offline. Furthermore, the system is capable of delivering a minimum guaranteed energy output—equal to the rated power for 15 minutes—which corresponds to 2.48 MWh net of efficiency losses (approximately the capacity of a single container).

Each will be coupled with a PCS group capable of working with the corresponding installed power, and each section will have a single interface power line to the MV side.

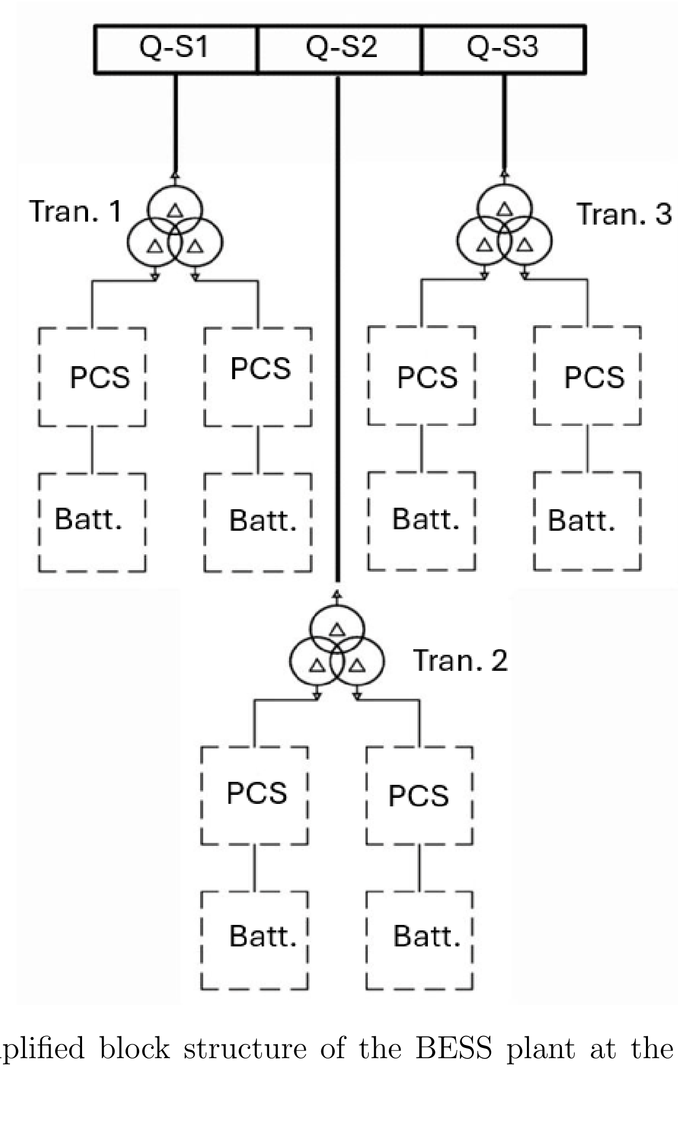

Figure 24: Simplified block structure of the BESS plant at the Moncalieri power plant

To better describe the installation, the next figures shows details from the plant drawings and final installation. In the figure you can see three 40' containers and three smaller 20' container. The battery containers and the conversion group containers have been stacked one on top of the other for space and practicality reasons. Due to the considerable weight of the batteries, they have been placed in the "groud floor" while the "first floor" container is reserved for the PCS group. This configuration appears clear from figure 26. The 20' container is designated for the transformer.

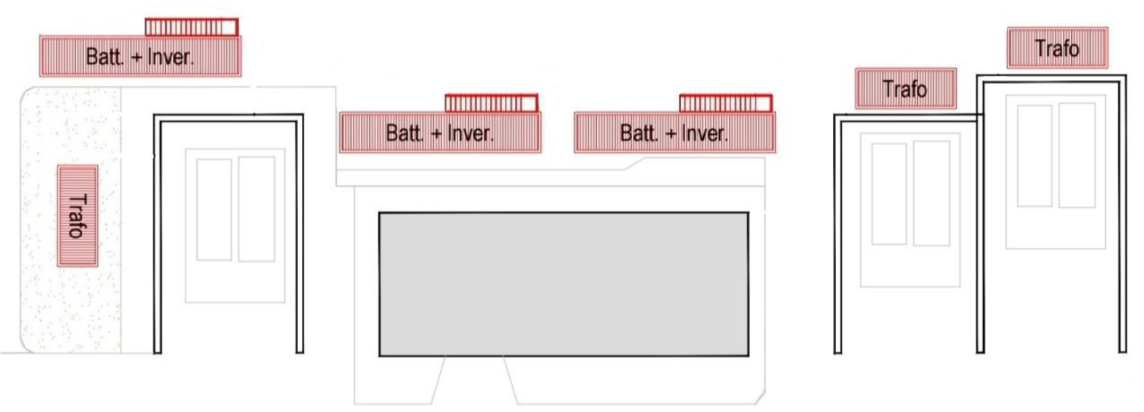

Figure 25: Layout of BESS from above

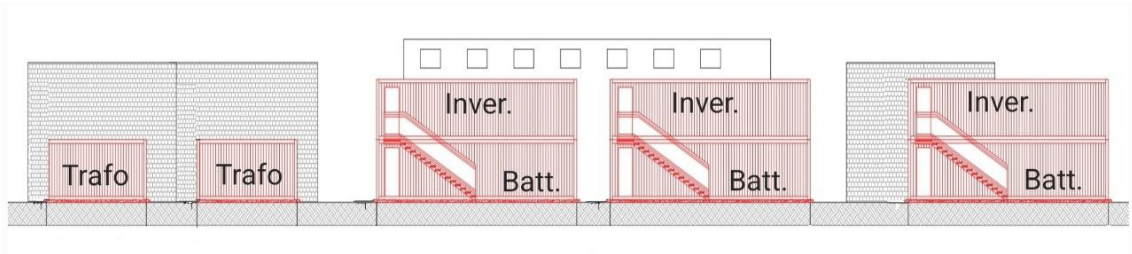

Figure 26: Layout of BESS from west

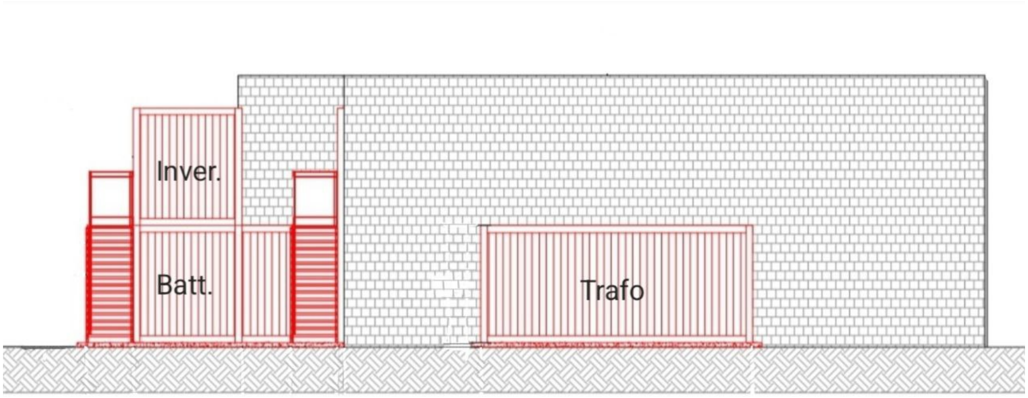

Figure 27: Layout of BESS from south

Such a complex system requires strict control: each module periodically measures and reports to the Battery Management System (or Battery Control System) to ensure operational safety and detect any faults. the control strategy is illustrated in figure 28 taken from the battery's specification.

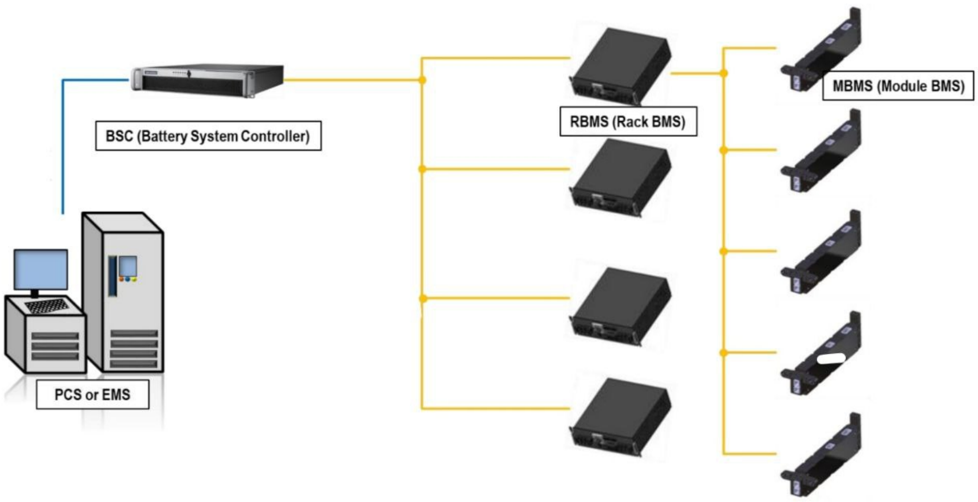

Figure 28: Hierarchical scheme for battery control system

2.1.2 Transformer

At the Moncalieri thermoelectric power plant there is a primary substation whose task is to transform the 132 kV high voltage, coming from the national transmission grid, into 27 kV medium voltage. This medium voltage value is a historical legacy, related to the original design of the power plant, which dates back several decades. Currently, a process is underway to unify the 22 kV medium voltage level, which is more common in new generation plants.

In order to connect the Battery Energy Storage System plant described, it is necessary to further lower the voltage from 27 kV to a level compatible with the low voltage used by the plant itself. For this purpose, the use of an additional transformer is necessary, or more precisly 3 additional transformers: one per battery subsystem previously presented. The the basic requirements to be met are collected in table 7.

	Value
Category	3-winding transformer MV/LV/LV
Nominal power	>110 % of Pn
Nominal voltage MV	27 kV
Nominal frequency	50 Hz
Efficiency	>99 %
cof PHI	0,85

Table 7: Transformer specifications

A three-winding MV/LV/LV transformer is preferred because it allows greater operational flexibility: the two parallel secondaries can be used to balance loads or to feed different branches of the BESS system separately, improving the reliability and redundancy of the system. Additionally a three-winding transformer saves on cost and space at the expense of a more careful design. The triple-winding type seleceted is shown in the figure 29: in this case it is as if the secondary is divided into two equal windings with the same voltage.

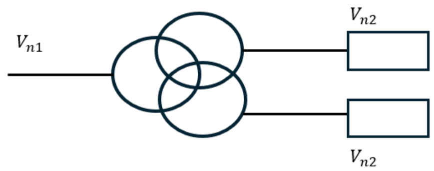

Figure 29: A 3-winding transformer scheme

A transformer with resin insulation and natural air cooling was chosen, whose characteristics are shown in the table 8.

	Values	Uom
Category	3-winding transformer MV/LV/LV	
Insulation type	resin	
N° phases	3	
Nominal power	4600	kVA
Nominal voltage MV	27 ± 2,5%	kV
Nominal voltage LV	430-430	Vac
Vector Group	Dd0d0	
Nominal frequency	50	Hz
Winding material	Al	
Temperature range	-25 ∼ +40	°C
Efficiency	99	%
cos φ	0,85	
cooling system	AN	
Short-circuit Impedence	>4%	
Protection class	IP00	
Weight	12 000	Kg

Table 8: Chosen Transformer rating plate data

To keep the temperature under control, thermistors with thermometric control unit are placed for remote temperature control: one on the central ferromagnetic core and one for each individual winding. All windings are delta connected, with no accessible neutral, to decrease harmonic content and robustness against faults. The diagram of the transformer in the figure 30 is shown.

Each of the three transformers will be connected via a medium-voltage cable to its own electrical panel in the 27 kV substation, which is directly connected to the primary substation of the power plant. The medium-voltage panel for each subsystem is essential, as it also serves as the interface point with the BESS control system. Inside the panel, measuring instruments are installed to support the management of the storage units.

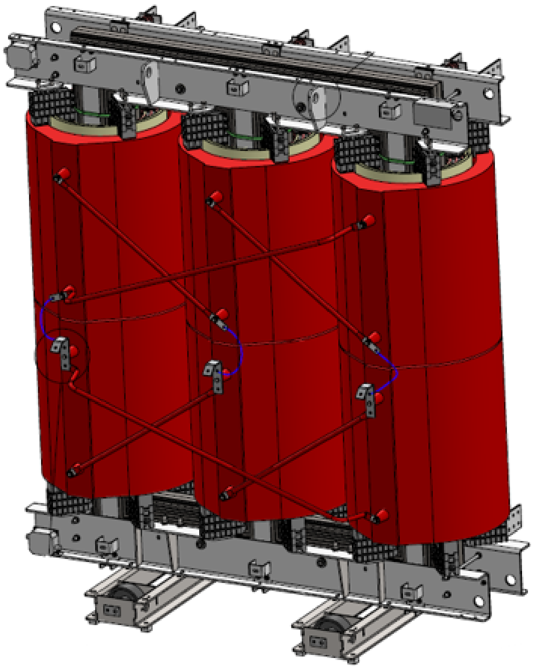

Figure 30: Chosen transformer for the Moncalieri BESS

2.1.3 PCS

The last key element to describe is the equipment inside the power conversion system. According to our calculations, the BESS delivers direct current at a voltage of 875.84 V, whereas the transformer operates with alternating current at a secondary voltage of 433 V. The inverters are responsible for performing this conversion, ensuring compliance with the requirements specified in the table 9

	Value
Nominal power	>110 % of Pn
Harmonic distorsion	<3%
Efficiency	$\geq$ 98%
Allowable overload	110%
Temperature range	-10° C $\sim$ +50 °C
Protection Class	>IP20

Table 9: Requirements for PCS

Following the principle of redundancy, it was anticipated that the rack of a subsystem are connected in parallel to two inverters and then to the transformer. The figure 31 shows the preliminary diagram by which the inverters inside a PCS container are connected.

Having triple-winding transformer allows us to divide the scheme into two parts of equal power and regulate them separately, with obvious advantages of flexibility and reliability. Each secondary winding of the TR (transformer) is connected to an inverter unit, which in turn consists of two inverters, brought into contact with each other by controllers.This is done to ensure that the stored energy can be accessed even in case of failure. In the figure above the inverter are denominated by the letter A,B,C,D to ease the comprehension.
It is mandatory to include manual-automatic circuit breakers with protection on both access points (DC and AC); in fact you can see switches and disconnectors in the diagram along with protective fuses.
In addition to these elements, there is also an electromagnetic filter in order to comply with the requirement on the harmonic component. It is essential that all waveforms that come in contact with the grid are extremely clean in order not to exacerbate the frequency problems that this system is supposed to be alleviating.
The scheme was achieved by using inverters with the following characteristics in table 10

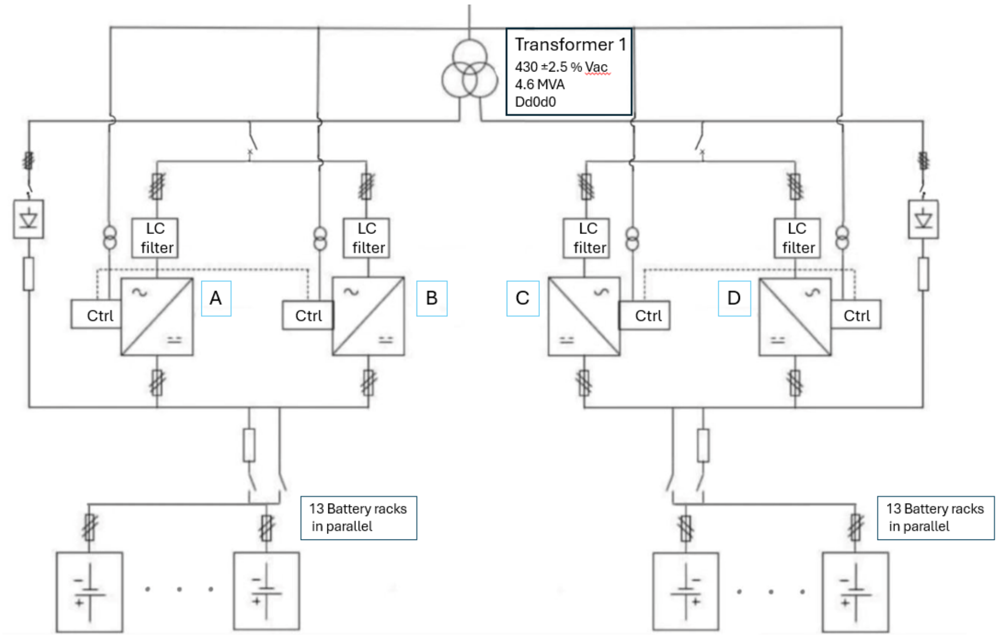

Figure 31: Preliminary electrical scheme for the PCS container

	Value	UoM
Max erogable power	11,6	MW
cos φ	0,85	
Efficiency	98%	%
Allowable overload	110% of Pn	
Temperature range	-10 ∼ +50	°C
cooling system	AF	
Protection class	IP 00	
Reaction time	200	ms
Weight	990	kg
Common DC max current	10	kA
Common AC max current	5800	A
Frequency	50/60	Hz

Table 10: Inverters specification

2.1.4 Cables

Let us consider the wiring of these systems for a moment. In order to carry out this project, certain conditions had to be met with regard to the sizing of the condutors.

- For the sizing of the power system cables, according to the voltage drop criteria, it was necessary to maintain the drop below
  - 4% at steady-stare regime
  - 10% at transient regime (max. 15sec)
- The minimum conductor cross-sections cannot be less than
  - 4 mm^2 for ammeter and voltmeter circuits
  - 2,5 mm^2 for power circuits
  - 1,5 mm^2 for control, interlocking and signaling circuits
- The grouping correction factor could not exceed 75%

In respect of these characteristics for all low voltage connections between plant systems, the following types of cable were used, all of which were laid by means of galvanized steel conduits or pipes.

Medium voltage	Unipolar RG7
Low voltage	Unipolar/ Multipolar FG16-0,6/1 kV
Auxiliary	FG17-0,6/1 kV

Table 11: Approved wires[25]

During the design of the plant, particular attention must be paid to power flows during the various operations, as regulated by CEI and Terna standards. For example,the standard CEI 0-16 [27], which governs how to connect active and passive users to the medium-voltage grid, requires the installation of interfacing devices between the components connected to the network—regardless of whether they are generators, BESS, or loads—in order to ensure that only waveforms within the allowable ranges are injected into the grid.
Another key regulation regarding frequency regulation from Terna needs to be mentioned. According to the frequency regulation [8], a distinction must be made between connections to the national transmission grid depending on the type of regulation being carried out (see figure 32 as a reference).
When the BESS is used for Fast Reserve regulation, it must have its own dedicated

high-voltage connection to the transmission grid, so that the injected power flow is unique and strictly controlled. This pathway is represented by the green path in the image.

Conversely, when the BESS is used for primary or secondary frequency regulation, the connection switch between the BESS and the rest of the power plant is closed, and the power from the BESS must pass through the same grid connection point used by the generation unit. Again, it is important to have a single power flow toward the grid. In this case, the power flow is represented by the red path.

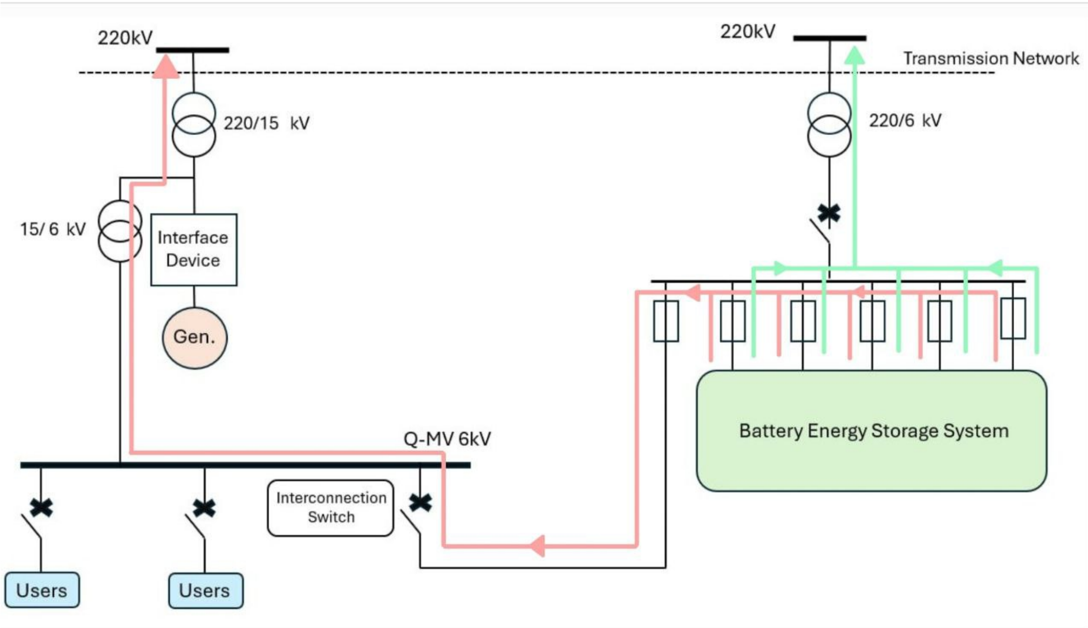

Figure 32: Simplified scheme of connections regarding frequency support

The schematic shown in figure 32 is indicative but approximately represents what happens during the switch in regulation mode. In reality, there are many more components and steps in the full schematic of the power plant, as the BESS was added to an already complex and completed environment, requiring these connections to be integrated accordingly. For this reason, a simplified diagram was used instead of an excerpt from the official technical drawings.

2.2 Turbigo

The Turbigo thermoelectric power plant initially built in 1967 stands in the area between the municipalities of Turbigo and Robecchetto Con Induno,in the province of Milan. Both municipalities are included in a protected area and managed by the Ticino Park Consortium, in fact in the areas close to the power plant there are building structures and facilities attached to agricultural activities with cultivated land or forested areas.

The power plant produces electricity with the TL800 combined cycle thermoelectric generating unit, connected at 400KV with the national transmission grid. The TL800 combined cycle consists of two gas turbines (nominal power 264 MW each) each coupled with an alternator to produce electricity. Being a combined cycle, the waste gases are sent to two recovery steam generators (HRSG) with post-combustion. Consequently the steam produced by each generator is in turn sent to a 330 MW steam turbine, which is also coupled to an alternator for power generation. Finally, the steam is condensed by harnessing the water from the "Naviglio Grande" and then re-emitted in a liquid state as an input to the two recovery steam generators.

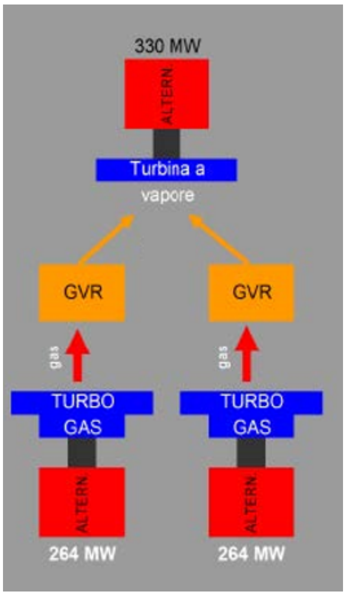

Figure 33: Strutcture of the TL800 combined cycle [11]

This power plant was purely used flexibly: it did not operate continuously but it was activated according to the needs of the national power system. It could be used to supplant energy during peak demand, to give frequency support to the grid or it was kept on standby (or 'cold reserve'), ready to be restarted in case of an emergency. Given the great support it provided and to improve the overall

efficiency of the power plant, it was decided in 2022 to upgrade it with another combined cycle : the TL400. It has similar operation to the TL800. It consists of a gas turbine with a unit capacity of 264MW (same as in the TL800) coupled with an alternator to generate electricity. The exhaust gases are invited to a recovery steam generator, and the resulting steam is in turn sent to a 430-MW steam turbine, related to another alternator. Here, too, the steam is condensed with water from the river to be reused.
The following sections will explain the components of the BESS plant installed at the facility.

2.2.1 Layout of the installed batteries

Again, the storage system must comply with the rules imposed by terna and the grid code to provide a storage system that provides the following characteristics

A numerical verification is provided here to demonstrate compliance with the power requirement. Considering the declared power registered in Terna's Production Unit Register (RUP) and assuming a minimum efficiency for the plant, the minimum required power must satisfy the relation 3 reported here with values already substituted.The value was conservatively rounded up to ensure conformity.

$$P_{min} = 1{,}5\% \cdot 1280 \cdot 70\% = 13,44 \tag{5}$$

Requider power	>14	MW
Required Energy	>12	MW
Deliverable energy at EOL	>7,2	MWh
Design life	10	Years
Round trip efficiency	>90	%
Inverter efficiency	>98	%
MT/BT Transformer efficiency	>98	%

Table 12: Minimum performance requested

For reasons of easier maintenance and cost savings, the same NMC lithium-ion cells used for the Moncalieri storage facility were chosen:the JP3 cell. Its specifications were given in the table 4. In order to reach the required amounts of energy and power, the following configuration was chosen.

- As before 2 groups of 14 ”JP3” cells in parallel constitute one pack with a capacity of 128 Ah and 51.52 V nominal voltage

- 24 modules in series constitute one rack, corresponding to a nominal energy of 158.2 KWh and a nominal voltage of 1236.48 V
- By arranging 85 racks in parallel it's possible to obtain the magnitudes shown in table 13

	Value	UoM
Rack in parallel	85	
Nominal Capacity	10,8	kAh
Nominal Voltage	1236,48	V
Voltage Range Usable		
Upper limit	1394,4	V
Lower limit	1008	V
Nominal Energy	13,45	MWh

Table 13: Obtained values

For safety reasons and to ensure some flexibility of the system this installed power is split into equal parts. The quantities described are divided into 5 completely independent subsystems where each section will be sized for about 20% of the total rated electrical power of the BESS.

By doing so, the operability of nearly 80% of the system can be assured even with one of the subsystems out of operation. The system is configured as shown in figure 34 while the relevant values are collected in table 14.

The BESS will also have to guarantee a minimum energy equal to the qualified power for a min of 15 minutes: the value should be around 3.5 MWh net of efficiency. All batteries are hierarchically controlled by the BMS and are equipped with temperature monitoring and fire suppression system.
Again, the batteries were placed in standard containers and for convenience the same ones used for Moncalieri were chosen. The dimensions are shown in the table 3. Given the floor plan of the Turbigo power plant elements, it was chosen to place the BESS inside a vacant building, named "Sala TV 1-2". All elements are arranged inside on elevated platforms.An excerpt from the design tables is shown in the figure 36 clearly showing the layout of the elements, while in figure 37 and 35 actual photos of the final design are depicted.

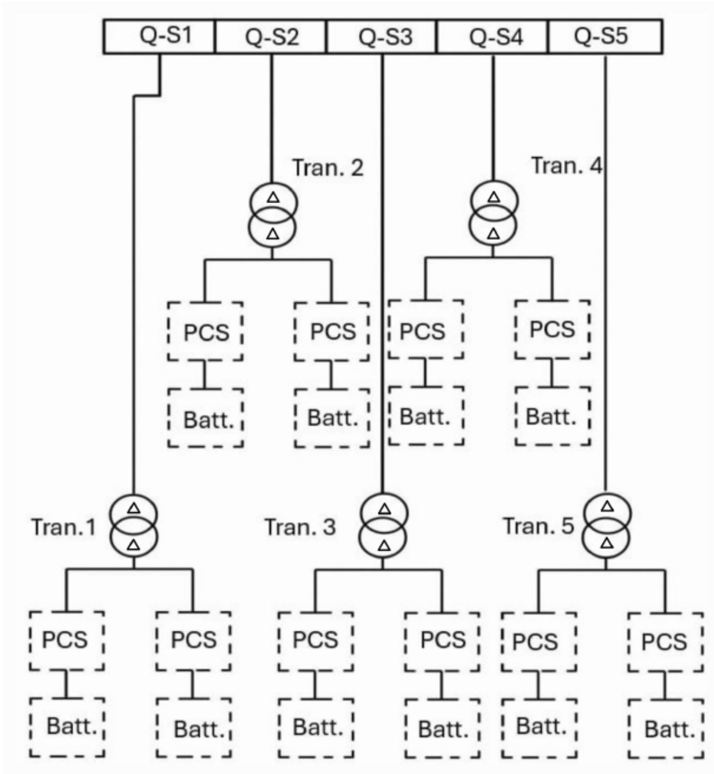

Figure 34: Simplified block structure of the subsystem in the Turbigo power plant

N° containers	5	
N°rack per containers	17	
Energy per rack	158,27	kWh
Nominal Capacity	184,96	kAh
Nominal Voltage	1236,48	V
Energy per container	228,70	MWh
Voltage Range Usable		
upper limit	1394,40	V
lower limit	1008,00	V
total Installed Energy	13,45	MWh
Total installed power	16	MW
Deliverable energy at EoL	10,84	MWh
Temperature range	$0 \sim 40$	$^\circ$ C

Table 14: Parameters per container

Figure 35: Photo of the transformer, PCS group and battery subsystem from the side

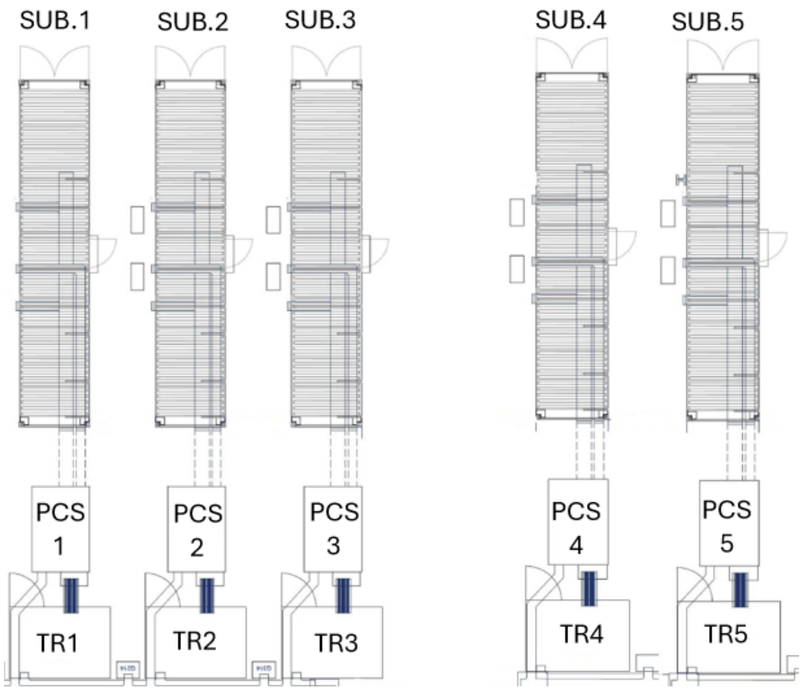

Figure 36: Excerpt form Turbigo design tables

Figure 37: Photo from above of the Sala TV 1-2

2.2.2 Transformer

Figure 34 illustrates how the BESS system interfaces with the rest of the power plant. The connection is made at the 6 kV medium-voltage switchboard via five dedicated MV lines, each serving one of the BESS subsystems. Each of these lines is connected to its own switchboard with its own switches and energy delivered/absorbed meters. An elevating/lowing transformer must be defined to ensure a safe and effective connection.
The following characteristics are sought

	Value	UoM
Category	2-winding transformer MV/LV	
Nominal power	>110 % of Pn	
Nominal voltage MV	$6 \pm 2 \cdot 2{,}5\%$	kV
Nominal frequency	50	Hz
Efficiency	>99	%
cof PHI	0,85	

Table 15: Required Specification

For practical reasons it was selected a two-winding transformer. A unit from the same supplier used for the Moncalieri project was selected, featuring the nameplate specifications in table 16. Also to keep the temperature under control, thermoprobes were again used with remote control on the magnetic core and windings.

Since the arragement is indoor, it's not required a high level of protection class, but for the safety of both staff and equipment, the transformer was located inside a protective grid as can be seen in the figure 38.

	Value	UoM
Insulation type	resin	
N° phases	3	
Nominal power	3,85	MVA
Nominal voltage MV	6 ± 2*2,5%	kV
Nominal Voltage LV	630	Vac
Vector Group	Dd0	
Nominal frequency	50	Hz
Winding material	AL	
Temperature range	-25 ∼ 40	°C
Efficiency	>99	%
cos φ	0,85	
Cooling system	AN	
Impedance	8	%
Protection class	IP 00	
Schort circuit voltage	7,43	%

Table 16: Nominal values for the chosen tranformer

Figure 38: Detail of the Turbigo Tranformer

2.2.3 PCS

From the configuration built in the paragraph 2.2.1, the voltage value at which the batteries work is known :1236.5 V in continuous supply. It is necessary to choose a suitable conversion unit to safely handle those values of installed energy. The required characteristics are collected in the table 17.

Nominal power	>110% of Pn
Harmonic distorsion	<3%
Efficiency	>98%
Allowable overload	110%
Temperature range	-10° C ∼ +50 °C
Protection class	IP20

Table 17: Required quantities for the PCS system

A particular solution was chosen for this installation: a modular inverter, typically used for photovoltaic systems.
It is composed of independent inverter modules, each of which can work independently and is designed to offer scalability, flexibility of use, and simplified maintenance. The inverter group that was selected includese 4 converter units, called field replaceable units (FRUs). These modules have a life expectancy of 30 years of operation even outdoors since they come with IP 55 protection class. This solution offers the advantages of both a string inverter and a contralized inverter because although each of them can work independently and is equipped with an MPPT, they are all connected at the extremes and in case of failure the different FRU can simply be disconnected and replaced.

	Value	UoM
Nominal power	4010	KVA
Temperature range	-35 ∼ 60	°C
Efficiency	98,9	%
Allowable overload	110% of Pn	
cooling system	AF	
Protection class	IP 55	
Voltage at the AC side	630 ± 10%	V
Voltage at the DC side		
Upper limit	1500	V
Lower limit	891	V
Frequency	50	Hz

Table 18: Nominal specification for the chosen inverters

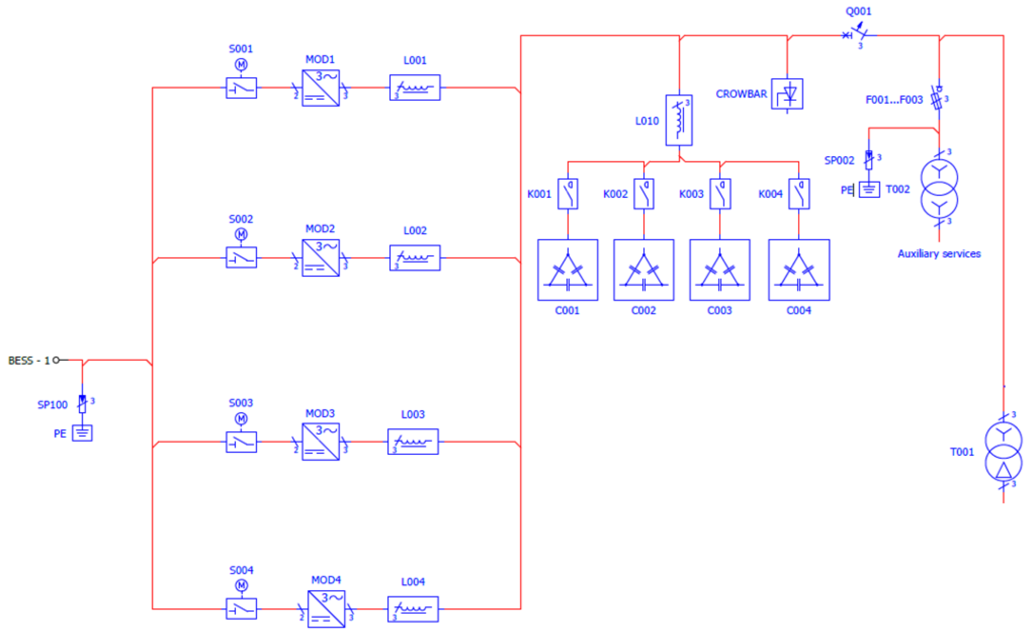

Figure 39: Connection inside the PCS system

The nameplace value for the PCD group are enlisted in table 18 while in figure 39 is included the single-line diagram of the PCS group in which one can see the four FRU modules connected at one end to the batteries meanwhile at the other end they

are going to connect with the LV/MV transformer. Appropriate safety measures in accordance with the law, such as fuses and disconnect switches, have been added to the PCS assembly, which can be identified in the above image. In addition, a CROWBAR circuit can be seen which is an additional overvoltage protection system: if it detects a dangerous voltage it creates a controlled short circuit by tripping the fuses. The image also shows the branch point with which the auxiliary support systems are fed.
The external case of the converters is shown in the photo shown in figure 46 where it's possible to see the vents for the forced air cooling.

Figure 40: External IP 55 for the PCS system

2.2.4 Cables

The same considerations made in paragraph 2.1.4 apply to the cables used for BESS in Turbigo, since both projects were executed following the Terna's regulations for partecipating in the UPI project [24].

2.3 Future options at the Turbigo power plant

The Turbigo plant has ambitions to expand further in the future, making the most of its strategic position in the power grid. The goal is to strengthen its role in grid services and, at the same time, generate new revenue opportunities. With this in mind, a decision has been made to install new BESS (Battery Energy Storage System) units, with the main objective of providing primary frequency regulation support.

In the next chapter, a preliminary design for a new storage facility will be presented, to be integrated with the BESS previously installed in 2022 and already described. Since this is a preliminary phase, we will not go into the practical details of the installation, but will provide a guideline on how the project can be developed in the future.

It should also be considered that the potential for an additional BESS system is manifold. Given the availability of ample space at the Turbigo site, the construction of a large photovoltaic system has also been assumed. In that case, the new BESS could also be configured for energy time-shifting functions, thus contributing to more efficient management of generation and feed-in.

3 Preliminary Project

In cooperation with the company IREN Energia, a request has been made to develop the preliminary design for a new Battery Energy Storage System plant, to be installed inside of the same buildings at the Turbigo power plant site where the precedent BESS was positioned. The design hypothesis assumes an indoor installation setup and must be adapted to take into account the elements of the BESS already been presented in section 2.2.

Since the final goal of the installation has not yet been defined, some flexibility has been allowed in the battery regulation strategy, which will therefore not be addressed at this stage of the project. Instead, it is certain that the new storage system will have to integrate efficiently and harmoniously with the other storage systems already present at the power plant. To ensure compatibility, priority has been given to the uniformity and conformity of components to guarantee coordinated operation. Using the same components also provides significant cost and maintenance savings.The new BESS will have to comply with all current technical regulations by Terna and CEI, regarding support to power plants and primary regulation services[8].

3.1 Specification Requested

The possibility of future expansion of the installed storage capacity was already envisaged at the design stage of the 16 MW BESS plan. As evidence of this intention, two starts were provided within the medium-voltage switch-box, with the name *"Riserva"*, specifically left free to allow for the possible connection of additional battery containers. An excerpt of the logistic diagrams of the Turbigo plant will be shown in figure 41 below, where these arrangements are indicated by the green arrow. In addition, the following supply point data in table 19 are known.

	Valuea	Uom
Supply voltage	6	kV
Frequency	50	Hz

Table 19: Dati from the MV swhich-box

The new storage system requested from the client provides a nominal power of **6 MW**. At the time of the formal requests for the BESS, permits were requested for an installed capacity of 22-23 MW, so taking into account the first plant already built, IREN has the possibility to exploit the remaining megawatts without any further paperwork.Although a check can be made to ensure that this value meets

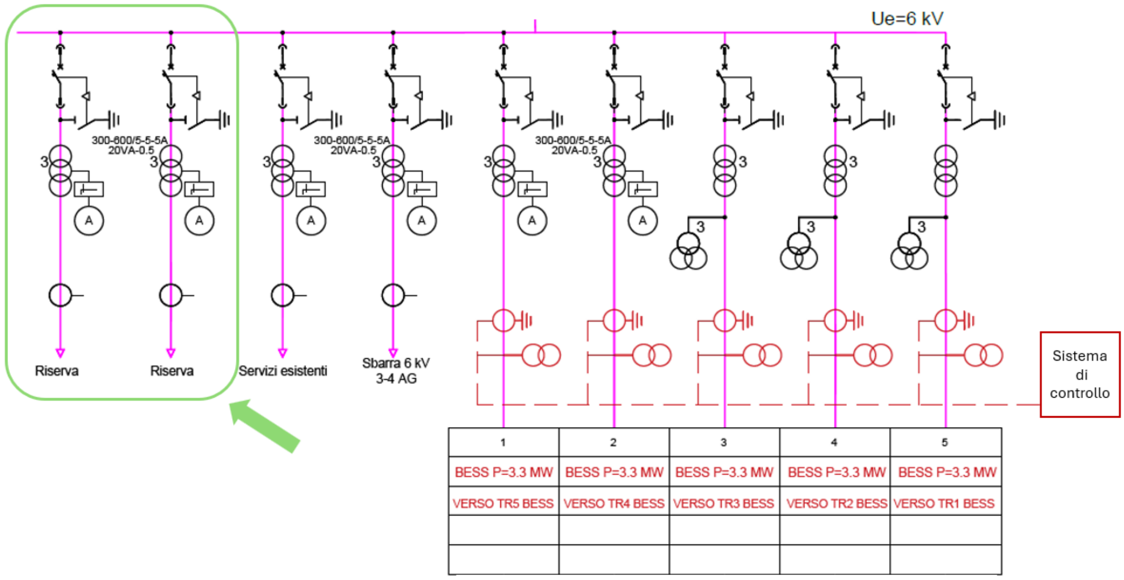

Figure 41: Excerpt of the logistic diagrams of the Turbigo Power Plant

the minimum requirement for frequency regulation support (as stated in paragraph 1.6.1), the criteria is less binding in this case. The new storage system will be integrated with the existing one, which fully complies with the prescribed regulatory limits.
Since the sum of the powers of the two systems allows the overall BESS system to meet the requirements imposed by the regulation, it is possible to proceed with the design of the new battery module.

3.2 Suggested Batteries Layout

Starting from a power needed of 6MW, we assume a dicharge rate of 1C. A C-rate represents the rate at which a battery can be charged or discharged and a 1C value corresponds to a reference value used in battery systems in industrial or commercial use. More importantly, it allows storage systems to deliver significant power in useful time without compromising battery life. Using the adopted C-rate, one can assume the need to install a storage system with a capacity of about 6 MWh. As mentioned in section 3 one of the objectives of this project is to maintain as much consistency as possible with the design choices adopted previously. For this reason, it was decided to use the same type of batteries used in the case of the Turbigo plant: Lithium-Ion cells with NMC technology, which technical data are given in the table 4.
To achieve the quantities required by the client starting from the selected cell, the

following configuration was assumed

- The 2s 14p pack already formed for Turbigo is selected, with a capacity of 128 Ah and 51.52 V nominal voltage
- 24 modules in series constitute one rack, corresponding to a nominal energy of 158.2 kWh and a nominal voltage of 1236.48 V. The same rack is likewise chosen so that similar voltage ranges are maintained when reaching the PCS assembly
- By arranging 37,9 racks in parallel it's possible to reach the quantities shown in table 20. The final value would be approximated by excess to 38 racks.

	Value	UoM
Rack in parallel	37,9	
Nominal Capacity	4,85	kAh
Nominal Voltage	1236,48	V
Voltage Usable range	1008 $\sim$ 1394,4	V
Nominal Energy	6	MWh

Table 20: Obtained values

Given the presence of two starts from the medium-voltage switchboard it's possible to follow the principle of redundancy with relative ease. It is proposed to create two specular subsystem with its own connection to the medium-voltage switchboard: each subsystem will have its own transformer and power conversion system, all of which will be linked to a single container with an installed battery capacity of around 3 MWh. This solution allows to comply with the principle of redundancy that was studied in the real case studies in the sec. 2, also manteining the flexibility of structure for the storage units. The proposed configuration for the storage units is summarized by the table 21, with 19 rack for container, and the ideal layout is illustrated in the figure 42.

N° rack in parallel	37,9	
approx.	38	
N° container	2	
Rack per container	19	
Capacity per container	2432	Ah
Energy per container	3,007	MWh
Total power	6,01	MW
Total energy	6,01	MWh
Deliverable energy at 10 years	5,41	MWh

Table 21: Proposed configuration

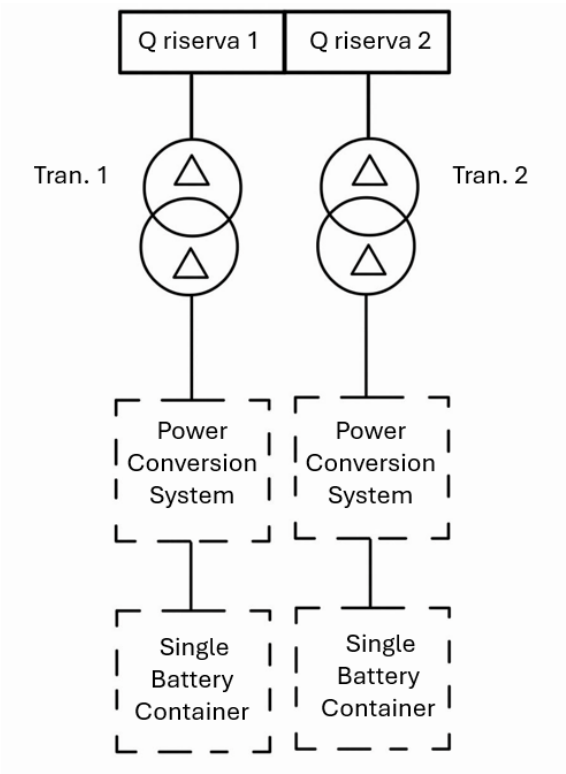

Figure 42: Proposed Block Diagram

The last value shown in the table 21 was obtained by analyzing the battery capacity decay curve provided by the manufacturer. This curve, presented in figure 43, clearly shows how, after ten years of operation, the residual capacity of the batteries decreases to 90% of the initial value. This parameter was considered to calculate the presented value.

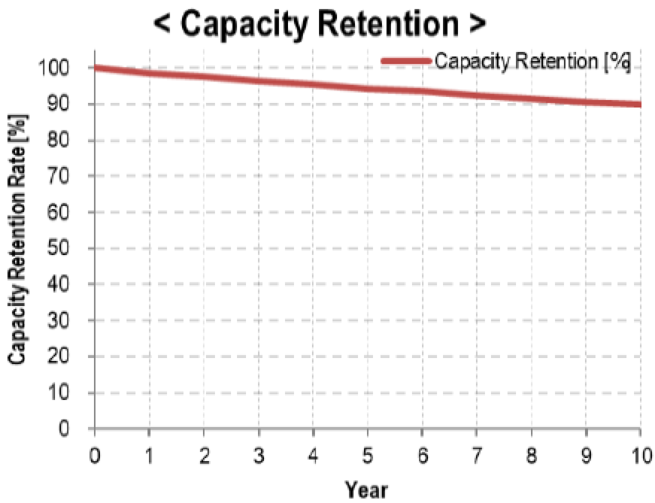

Figure 43: Capacity retention curve

The necessary calculations were carried out to verify the feasibility of the proposed solution, and due to the large number of racks planned, it became apparent that a larger size container was needed. Therefore, it is proposed to keep the same type of standard High Cube container used in the Turbigo plant, but in a 45-foot version, which is longer and slightly shorter. The dimensions of this container are given in the table 22 and are compatible with the overall footprint of the planned racks, also taking into account the additional space required for the installation of the fire and air conditioning systems.

	Value	UoM
Width	2352	mm
Length	13556	mm
Height	2700	mm
Weight	5050	kg

Table 22: Dimension for a 45' Standard ISO High Cube [28]

Figure 44: Proposed 45' standard container

As mentioned earlier, thermal management of batteries is a key aspect in ensuring their proper functioning and operational safety. Without proper temperature control, hazardous conditions, such as fire or explosion, can occur. For this reason, dedicated air conditioning units are to be installed inside the battery rooms to maintain the indoor temperature at optimal values. The nominal operating condition is 23± 4°C, but the air conditioning systems must be able to guarantee during active operation an indoor temperature of

- 25 °C when that outside temperature exceeds 35 °C
- 15 °C when the outside temperature falls below -10 °C.

Following the manufacturer's information, it is assumed that the battery will charge according to a CC/CV profile (costant current/constant voltage profile). In the first step, a constant current is applied until the nominal charging voltage of 1394,4 V is reached. Once this threshold is reached, the system switches to constant voltage mode, keeping the voltage stable while the current begins to gradually decrease. The charging phase ends when the current decreases to 6.4 A, the threshold below which the battery is considered fully charged.
During the discharge phase, energy is delivered in direct current, with the voltage gradually decreasing as the battery empties. The discharge process is considered completed when the minimum voltage of 1008 V is reached, a the lower limit set to protect the battery indicated in table 20.

It should be remembered that in order to allow frequency regulation on the power grid, as explained in sec 1.6, batteries should have some margin of availability on the energy they can quickly deliver or absorb, depending on the needs of the system. For this reason in the likely case where the batteries is use mainly for frequency regulation support it is chosen to keep the charge level of the batteries around **50% of their state of charge**. This ensures both the availability of energy to be delivered and the space to absorb energy in response to the change in the frequency. The description of charge and discharge profiles provided above is therefore intended for informational purposes only and not as a continuous mode of operation, although periodic charge/discharge cycles of batteries are recommended to preserve their storage quality.

3.3 Trasformer

The transformer to be chosen will be the connection point between the subsystems presented above and the medium-voltage substation.

For clarity, the 6kV medium-voltage station shown in figure 41 is directly connected to the 132kV transmission grid using a MV/HV transformer. Although the transformer itself will not be discussed in this text, it's adequate to spend a few words to describe the feeder whitin the MV switchboard. A detail of it is given in the figure 45.

Each riser is equipped with a circuit breaker, and followed by a measurement and protection system. In particular, it can be seen how the switch is connected with an interlock that connects the branch directly to ground. Below is a current transformer (TA) used for both measurement and protection, along with a voltage transformer (VT) featuring multiple secondary windings with the same goal.

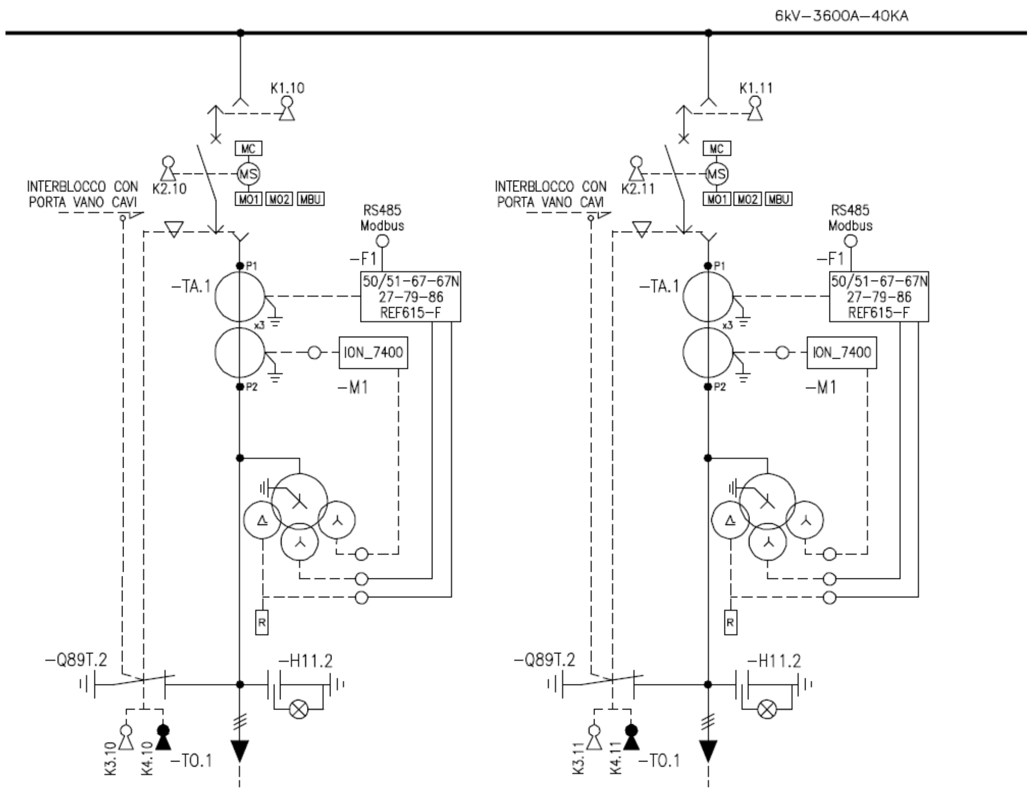

Figure 45: Detail of feeders associated with the planned BESS

To remain consistent with the design choices used in the present system, a single-winding transformer is chosen. Each transformer will correspond to a subsystem of batteries corresponding to 3 MW. Considering that the size of the subsystem is similar to that described in the section 2.2, it is intended to verify the possibility of reusing the same transformer model previously employed.

For the transformer to be used, it must satisfy two conditions:

- The size of the transformer must be larger than the size of the system downstream of the transformer. From case study experience, we know that it must meet the following condition

$$P_{TR} \geq 110\% \cdot P_N \tag{6}$$

- To keep the transformer within an optimal workload range, the following good practice design criteria is sought

$$\frac{2}{3} \cdot P_{TR} < P_N \cdot c_{loss} < \frac{3}{4} \cdot P_{TR} \tag{7}$$

Substituting the values illustrated in table 23 the conditions are met.

	Value	UoM
Apparent Power	3,85	MVA
Cos φ	0.85	
Active power	5,67	MW
P_N for subsystem	3,007	MW
110% of P_N	3,31	MW
Loss coefficient	1,3	

Table 23: Values needed for the verification

It's possible to chose the same transformer used in paragraph 2.2.2, suggested in similar layout: protection class IP00 with a protective metallic grid.

3.4 PCS group

After sizing the transformer we also want to identify the PCS assembly. Taking into account that the assumed subsystems have same voltage rating assumed for the pre-existing Turbigo system, that the required power is similar, and that we can use the same transformer chosen for the Turbigo plan(as demonstrated in the previous section) it's preferred to re-use the inverter group selected for the pre-existing plant. The complete table with the datasheet information was already presented in table 18 while the main values are given here to prove that the values provided by the subsystem are within the operating values of the selected PCS group, as to be expected.

	Value	UoM
Nominal power for the PCS	4010	kVA
Voltage at the AC side	630 +10%	V
Voltage at the DC side	891-1500	V
Nominal power for subsystem	3,007	MW
Nominal voltage of a rack	1236,4	V

Table 24: Operating values at the PCS group with the hypothetic set up

Figure 46: External IP 55 for the PCS system from datasheet

3.5 Cables

For the system to be properly outlined, it is not enough just to define the components, but in this section all the cable connections and their respective protections, which guarantee safe operation, are going to be presented.

To simplify the exposition of the work we will go over the wiring starting with a single rack and ending with the transformer. It was considered starting from the rack furthest from the switchboard so that the cable can be sized in its most disadvantageous condition.

The following connections will be illustrated:

- The cable connecting the single battery rack to the LV switchboard inside the subsystem
- The line connecting the LV switchboard of the batteries to the PCS unit
- The cable connecting the switchboard of the PCS to the transformer

The table 25 includes a hypothetical of the lengths of the installation environment taking into account the available space and the selected container as illustrated by figure 47. All lengths have been lengthened by 10% to account for occasional trimming for curves or waste of space.

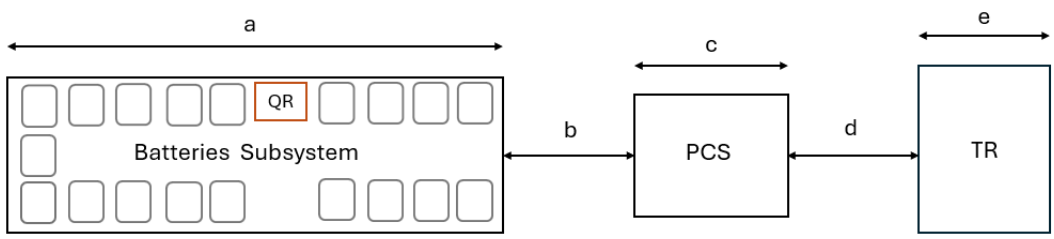

Figure 47: Hypothetical Configuration

	Assumed formula	Length with 10% increase (m)
Rack to Q-LV	$\frac{a}{2}$	6.778
Q-LV to PCS	$\frac{a}{2} + b + \frac{c}{2}$	7.137
PCS_TR	$\frac{c}{2} + d + \frac{e}{2}$	0.4

Table 25: Lengths of segments with 10% increase

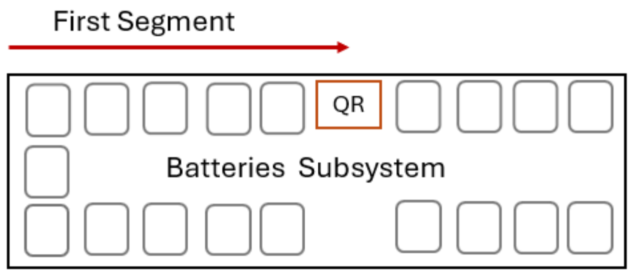

Figure 48: First segment considered

The first cables to be selected are indicated by figure 48 for better understanding. This connection interact directly with batteries, so they will have to be cables suitable for DC transmission. For this reason, low voltage cables for photovoltaic system application have been chosen from “Com Cavi S.p.a ” illustrated in figure 49.
They are designed both for indoor or outdoor power transmission and have an optimal service life of at least 25 years under normal operating conditions. As can be deduced from the class to which they belong, they are cables with good flame resistance, which produce little smoke, do not release incandescent droplets, and in the event of an overcurrents emit low-toxic gases.The table 26 shows the functional characteristics of the chosen cable.

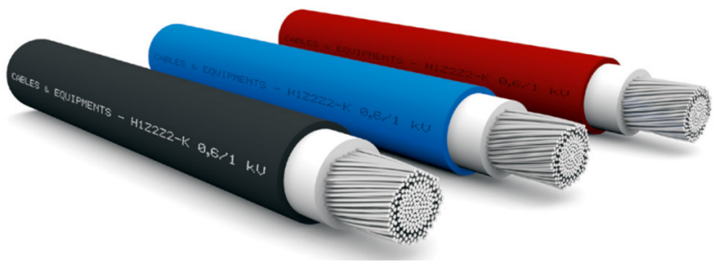

Figure 49: Cables from Cam Cavi S.p.a.

	Value	UoM
Class	Cca-s1b,d1,a1	
Conductor	Flexible tinned copper	
Insulation	Halogen-free elastomer quality Z2	
Outer Casing	Halogen-free elastomer quality Z2, in colors black, red and blue	
Nominal Voltage AC	1	kV
Nominal Voltage DC	1,5	kV
Maximum Voltage AC	1,2	kV
Maximum Voltage DC	1,8	kV
Maximum Operating temperature	90	°C
Minimum Installation temperature	-25	°C
Maximum short-circuit temperature	250	°C

Table 26: Data from ComCavi S.p.a. [13]

The following considerations are provided to support the design choices.
According to the operating conditions on the datasheet of the battery rack, the nominal current entering or exiting each rack is 64 A. It's assumed the system operates in a temperature-controlled environment in order to protect the quality of the batteries and it's considered a temperature around 25°C.
Since batteries uses direct current (DC), two cables are required for each rack: one for the supply and one for the return. To ensure clear identification, red cables are used for the supply, generally referred as positive, and black cables for the return, generally referred as negative.
For cable sizing, the following correction factors have been applied:

- A temperature correction factor of k_1 = 1,04, accounting for the ambient temperature different from 30° C for EPR-insulated cables
- A grouping factor of k_2 = 0,75, based on previous system designs, corresponding to a maximum of five cables laid together on horizontal or vertical perforated trays.

Using these parameters, the required cable cross-sections and current-carrying capacities were calculated. The results are presented in the table 27.

	Cable for supply	Cable for return	UoM
Chosen Cable	H1Z2Z2-k Red	H1Z2Z2-k Black	
Number of cables	1	1	
Section	16	16	mm^2
From	Furthest Rack	Furthest Rack	
To	QR- LV	QR- LV	
Voltage	1236.4	1236.4	V
Use Current I_b	64	64	A
Current with the correction coefficients I_n	82.05	82.05	A
Cable rating I_z	107	107	A
Voltage drop (c.d.t.)	0.0934	0.0934	%
Average cable weight	132	132	kg/km
Electrical resistance	1.21	1.91	Ω/km
Installation Type	43	43	

Table 27: Values calculated from the rack to the Low Voltage switchboard

It is worth noting that in direct current it is used a simplified form of the percent voltage drop, derived directly from Ohm's law that can be calculated as

$$\%\Delta V = \frac{2 \cdot I \cdot R \cdot L}{V_n} \cdot 100 \tag{8}$$

In this case the conductor behaves as a purely resistive element, so the voltage drop depends only on material properties, length, cross-section and current. Since DC has no frequency component, inductive and capacitive effects are absent and the current has no phase displacement. The expression is therefore linear and straightforward, but it's fondamental to consider che calculation twice, in order to considerate both the positive and negative cable.

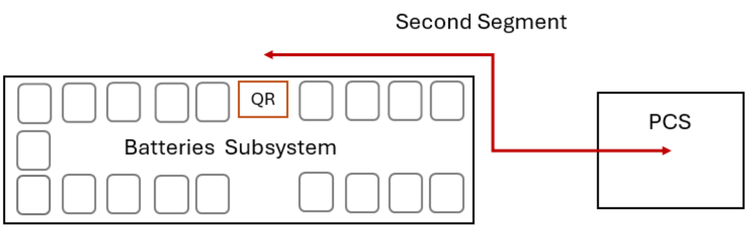

Figure 50: Second segment considered

The second segment, depicted in figure 50, is always a DC connection that in this case connects the LV switchboard with the conversion unit. This time the operating current to consider is coming from the 19 racks so it's to be considered a total current of 1216 A. In order to improve safety and decrease costs it was choosen to split the elevated current into 4 single-core cables always in installation type 43. Following CEI regulations it indicates a

> "Single-core cables with sheathing and multi-core cables laid in open or ventilated tunnels, with horizontal or vertical routing" [29]

For the correction coefficients we keep the same values as before so we can draw the conclusions shown in the table 28

	Cable for supply	Cable for return	UoM
Chosen Cable	H1Z2Z2-k NERO	H1Z2Z2-k ROSSO	
Number of cables	4	4	
Section	150	150	mm^2
From	QR-LV	QR-LV	
To	PCS	PCS	
Voltage	1236.4	1236.4	V
Use Current I_b	304	304	A
Current with the cor. coefficients I_n	389,74	389,74	A
Cable rating I_z	453	453	A
Voltage drop (c.d.t.)	0.0498	0.0498	%
Average cable weight	1460	1460	kg/km
Electrical resistance	0,129	0,129	Ω/km
Installation Type	43	43	

Table 28: Values calculated for the line from the Low Voltage switchboard to the PCS Group

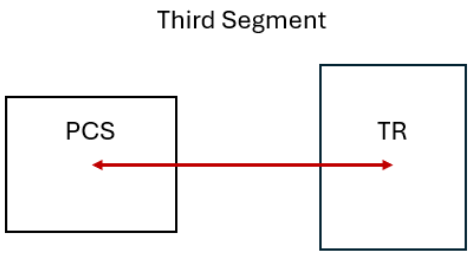

Figure 51: Third segment considered

The third line to be described is the last connection of the singular subsystem: the link from the PCS output to the transformer, as shown in figure 51.
In this case we are dealing with AC transmission so a different type of cable is chosen, shown in figure 52. A three-core flexible copper cable with rubber insulation and PVC outer sheath was selected. As can be deduced from its classification it has good resistance to industrial oils and greases, has a low emission of corrosive gases, and because of its properties of limiting fire development and heat emission it is suitable for power supply in civil works. Full relevant functional characteristics are given in table 29

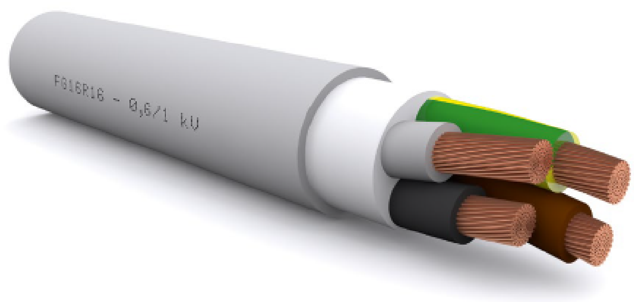

Figure 52: Figure taken from the datasheet of the AC cable chosen [12]

	Value	UoM
Class	Cca-s3,d1,a3	
Conductor	Flexible copper wire	
Insulation	Rubber Compound G16	
Outer Casing	grey PCV	
Total Cabling	The cores are stranded together in concentric lay	
Rated Voltage AC	600-1000	kV
Rated Voltage DC	1,5	kV
Maximum Operating temperature	90	°C
Minimum Operating temperature	-15	°C
Maximum short-circuit temperature	250	°C
Maximum tensile stress at the cross section of the wire	50	N/mmˆ2

Table 29: Data taken from the datasheet of the AC wire [12]

In this case since the outer sheath is made of PVC(and not EPR as for the previous cable) the correction coefficient for temperature will be $k_1 = 1.06$ while the cramming coefficient remains the same since it is indicated as the preferred number by both the experimental studies and the customer's request. It corresponds to a maximum of 5 cables in layer in the same laying.
The output current from the PCS group is calculated according to the formula of AC transmission

$$I = \frac{P}{\sqrt{3} \cdot V \cdot \cos\varphi} \tag{9}$$

where :

- V is the output voltage at the exit of the PCS
- P is the maximum active power produced by the batteries
- cos φ is defined by the characteristics of the inverter group

while the industrial voltage drop for an AC cable is calculated according to the complete formula given below

$$\%\Delta V = \frac{\sqrt{3} \cdot I \cdot L \cdot (r\cos\varphi + x\sin\varphi)}{V} \cdot 100 \tag{10}$$

In this case the conductor cannot be considered purely resistive but the voltage drop depends on the reactance of the line other than the resistance. The reactance includes both inductive and capacitive effects distributed along the conductor as can be seen from the formula. Those values need to be provided by the manufactor of the cables. This comprehensive approach ensures an accurate evaluation of voltage variations under real operating conditions in industrial AC systems.
Installation type 61 was chosen, which according to CEI 64-8 indicates

> "Single-core sheathed cables and multi-core cables laid in buried protective tubes or underground tunnels" [29]

In the present case, these are buried three-core cables with a soil thermal resistivity of K= 1 Km/W. Given the high current, it was chosen to transmit it in three tubes containing 5 cables each sized as expressed in table 30.

	Cable for supply	UoM
Chosen Cable	FG16R16	
Number of cables	15	
Section	150	mm^2
From	PCS	
To	Transformer	
Voltage	630	V
Use Current I_b	216,14	A
Current with the cor. coefficients I_n	271,87	A
Cable rating I_z	288	A
Voltage drop (c.d.t.)	0,0035	%
Average cable weight	5404	kg/km
Electrical resistance	0,129	Ω/km
Electrical reactance	0,0745	Ω/km
Installation Type	61	

Table 30: Values estimated for the line from PCS to the transformer

Although this may be an acceptable solution, we would also like to propose a secondary solution: the use of busbars.

Figure 53: Tipical straigh element for a busbar

Given that the total current at this point in the system exceeds 3200 A, the use of busbars makes a lot of sense. For example in figure 54 there is an excerpt from the datasheet for a type of busbar that has been selected and is currently on the market: with an AC voltage rating of up to 1000V, this type of busbar can withstand currents of up to 6300 A making it an ideal solution for high currents.

<table>
<tr><th rowspan="2">Raating [A]</th><th colspan="2">XCP-S</th><th colspan="2">XCP-HP</th></tr>
<tr><th>ALUMINIUM</th><th>COPPER</th><th>ALUMINIUM</th><th>COPPER</th></tr>
<tr><td>630</td><td rowspan="6">S</td><td>-</td><td rowspan="6">S</td><td>-</td></tr>
<tr><td>800</td><td rowspan="5">S</td><td rowspan="6">S</td></tr>
<tr><td>1000</td></tr>
<tr><td>1250</td></tr>
<tr><td>1600</td></tr>
<tr><td>2000</td></tr>
<tr><td>2500</td><td rowspan="3">D</td><td rowspan="4">D</td><td rowspan="3">D</td></tr>
<tr><td>3200</td><td rowspan="3">D</td></tr>
<tr><td>4000</td></tr>
<tr><td>5000</td><td>T</td><td>T</td></tr>
<tr><td>6300</td><td>-</td><td>T</td><td>-</td><td>T</td></tr>
</table>

Figure 54: The graph shows the temperature ranges endurable by their manufactured bar

In particular, we recommend the XCP-HP type produced by the "Bticino" company [30]. It is a busbar system characterised by higher performances on energy saving, in fact it is considered ideal for heavy duty application where high energy efficiency is required. Furthermore it is designed to work at 50°C of ambient temperature and even higher.

One of the disadvantages of this technology is that, since the bars are rigid, the design of the tracks is more complex. The bars are sold in vertical, horizontal, or angled pieces (some of which are presented in figure 55) to adapt to the most convenient routes, but they are obviously less flexible than cables. Although the initial cost is high, it is ultimately a good investment for high currents. Moreover they also usually cause a smaller drop in voltage.

Figure 55: Some of the elements sold to built the cable's tracks

Since in the existing Turbigo project it was decided to use cables instead of busbars, the same technology was chosen for the current project, the calculations for which are shown in table 30 above. It was verified that the overall voltage drop from the battery subsystem to the transformer was below reasonable limits and was below 0.2% so the sizing is considered acceptable. Although the cables presented in this section were chosen with reference to one subsystem, they will be applied uniformly to connections involving the second battery subsystem. This will ensure consistency in design and performance across both sections.
The cable connecting the transformer to the medium-voltage substation has not been studied, as it is obvious that it will be chosen in accordance with the other cables already in the substation.

3.5.1 Tables from Datasheet

For the sake of accuracy and considering the complexity of the catalogs selected, the tables used to perform the calculations for cable sizing are here provided.

Formation Formazione	Ø approx. conducteur Ø indicativo conduttore	Épaisseur moyenne isolant Spessore medio isolante	Épaisseur moyenne gaine Spessore medio guaina	Ø. approx. production Ø indicativo produzione	Poids approx. câble Peso indicativo cavo	Résistance électrique max à 20°C Resistenza elettrica max a 20°C	Intensité admissible à l'air libre / Portata di corrente in aria libera: Câble seul Singolo cavo 60°C	2 câbles adjacents 2 cavi adiacenti 60°C
n° x mm²	mm	mm	mm	mm	kg/km	ohm/km	A	A
1 x 1,5	1,5	0,7	0,8	4,7	34	13,7	30	24
1 x 2,5	2,1	0,7	0,8	5,2	47	8,21	40	33
1 x 4	2,5	0,7	0,8	5,8	58	5,09	55	44
1 x 6	3,0	0,7	0,8	6,5	80	3,39	70	70
1 x 10	4,0	0,7	0,8	7,9	127	1,95	95	95
1 x 16	5,0	0,7	0,9	8,8	180	1,24	130	107
1 x 25	6,2	0,9	1,0	10,6	270	0,795	180	142
1 x 35	7,6	0,9	1,1	12,0	360	0,565	220	176
1 x 50	8,9	1,0	1,2	14,1	515	0,393	280	221
1 x 70	10,5	1,1	1,2	15,9	720	0,277	350	278
1 x 95	12,5	1,1	1,3	17,7	915	0,210	410	333
1 x 120	13,7	1,2	1,3	19,8	1160	0,164	480	390
1 x 150	16,1	1,4	1,4	21,7	1460	0,132	566	453
1 x 185	17,7	1,6	1,6	24,1	1780	0,108	644	515
1 x 240	19,9	1,7	1,7	26,7	2310	0,082	775	620

Figure 56: Data for the first and second segment presented [13]

Formazione Size	Ø indicativo conduttore Approx. conduct. Ø	Spessore medio isolante Average insulation thickness	Spessore medio guaina Average sheath thickness	Ø esterno massimo Max outer Ø	Peso indicativo cavo Indicative cable weight	Resistenza elettrica max a Max electrical resistance at 20° C	Portata di corrente / Current rating A: in aria a / in air at	in tubo in aria a / in pipe in air at	interrato a / Underground at 20° C		in tubo interrato a / In underground pipe at 20°C	
n° x mm²	mm	mm	mm	mm	kg/km	Ω/km	30° C	30°C	K=1	K=1,5	K=1	K=1,5
Tripolari/3 cores												
3 x 1,5	1,5	0,7	1,8	12,5	150,0	13,30	23,0	19,0	23,0	22,0	20,0	19,0
3 x 2,5	2,0	0,7	1,8	13,6	190,0	7,98	32,0	26,0	30,0	29,0	27,0	25,0
3 x 4	2,5	0,7	1,8	14,9	250,0	4,95	42,0	35,0	39,0	37,0	34,0	32,0
3 x 6	3,0	0,7	1,8	16,2	320,0	3,30	54,0	44,0	50,0	47,0	43,0	41,0
3 x 10	4,0	0,7	1,8	18,2	470,0	1,91	75,0	60,0	67,0	63,0	58,0	55,0
3 x 16	5,0	0,7	1,8	20,6	640,0	1,21	100,0	80,0	88,0	83,0	76,0	72,0
3 x 25	6,2	0,9	1,8	24,5	960,0	0,798	127,0	105,0	113,0	107,0	99,0	93,0
3 x 35	7,4	0,9	1,8	27,3	1290,0	0,554	158,0	128,0	139,0	131,0	121,0	114,0
3 x 50	8,9	1,0	1,8	31,2	1785,0	0,386	192,0	154,0	172,0	162,0	149,0	141,0
3 x 70	10,5	1,1	1,9	35,6	2700,0	0,272	246,0	194,0	212,0	200,0	184,0	174,0
3 x 95	12,2	1,1	2,0	40,0	3410,0	0,206	298,0	233,0	251,0	237,0	218,0	206,0
3 x 120	13,8	1,2	2,1	44,4	4340,0	0,161	346,0	268,0	290,0	274,0	252,0	238,0
3 x 150	15,4	1,4	2,3	49,5	5404,0	0,129	399,0	300,0	332,0	313,0	288,0	272,0
3 x 185	16,9	1,6	2,4	55,2	6550,0	0,106	456,0	340,0	373,0	352,0	324,0	306,0
3 x 240	19,5	1,7	2,6	61,9	8475,0	0,0801	538,0	398,0	439,0	414,0	382,0	360,0
3 x 300	23,0	1,8	2,8	68,0	10440,0	0,0641	621,0	-	-	-	-	-

N.B. I valori di portata di corrente sono riferiti a: n°3 conduttori attivi - Profondità di posa 0,8 m per i cavi interrati
N.B. Current rating values are refered to: n° 3 loaded conductors - Installation depth for underground cables 0,8 m

N.B. K=1: resistività termica del terreno 1,0 K.m/W
K=1,5: resistività termica del terreno 1,5 K.m/W
N.B. K=1: thermal resistivity 1,0 K.m/W
K=1,5: thermal resistivity 1,5 K.m/W

Figure 57: Data for the third segment presented [12]

3.5.2 Safety measures

In order to complete the elaboration, it was also planned to propose safety measures for the cables. Protections are thought as arranged in figure 58 meaning

- one fuse for each rack
- two fuses for the second segment, one for the positive line the other for the negative
- one thermomagnetic circuit breaker for the third segment

Taking into account the current values expressed in the tables of section 3.5, the raccomanded elements are here presented.

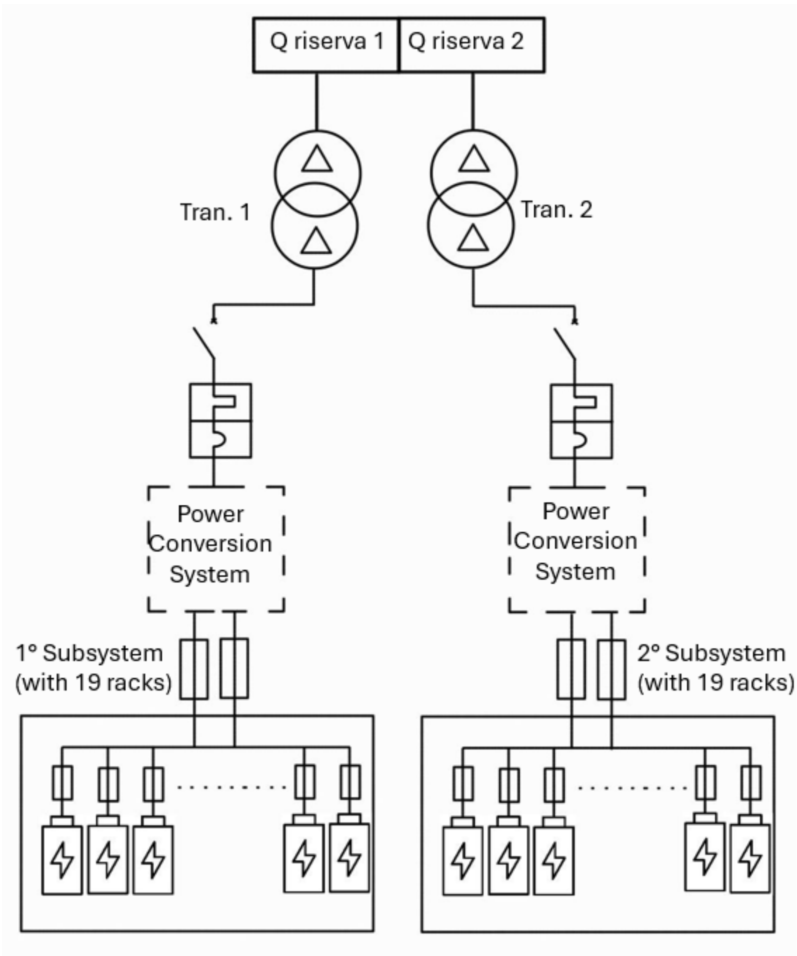

Figure 58: Suggested protection system for cables

For DC cable protection it was selected batteries' fuses, constructed to withstand DC voltages up to 1500 Vdc and have a breaking power of up to 100KA.
Shown in figure 59 the fuses type gBAT of the "ITALWEBER" brand, are specifically designed for the protection of battery systems. There are different sizes of them so it was selected the NH-1XL size with rated current 80 A for the fuse connected to the rack and the NH-3L size with rated current 400 A for the cables coming out of the subsystem.

Figure 59: Photo the fuse taken from the datasheet [14]

Name	NH fuses for batteries
Product Type	Blade type fuses for battery protection
Characteristic curve	gBAT
Size	NH-1XL and NH-3L
Body	Steatite
Contacts	Silver
Rated current (A)	50- 630
Rated voltage DC (V)	1500
Breaking capacyty	100 kA

Table 31: General Characteristics of the fuse [14]

One should be placed for each rack and one for each cable exiting the subsystem so that the fault can be easily isolated.
For AC wiring, the use of boxed circuit breakers is suggested. The Tmax series of boxed circuit breakers from ABB was taken into consideration because their range

of use in AC varies from 1 A to 630 A with voltages up to 690 V. In particular, type T4 was selected, which includes thermomagnetic circuit breakers with individually adjustable thermal and magnetic thresholds and can interrupt short-circuit currents up to 120KA. The boxed circuit breaker, in conformity to the IEC Standard 60947, is shown in the figure 60

Figure 60: Picture taken from the datasheet of the switch [15]

Name	Tmax
Product Type	individual thermomagnetic circuit breakers
Size	T4
Rated current (A)	250-320
Rated voltage DC (V)	690
Breaking capacity	120 kA
Frequency(Hz)	50-60

Table 32: Summary of the general characteristics of the Tmax circuit breaker [15]

It should be noted that the conversion system chosen is a modular system, meaning that it consists of 4 individual inverters. It appears clear studying the line diagram of the PCS extracted from the datasheet of the component and shown in figure 8. Neither the cables nor the safety measures for that section are sized because it is assumed that being within a closed assembly sold already boxed in it is already included the safety measures necessary for optimal operation.

3.6 Single-line diagram of the proposed BESS system

After having addressed all the components of the system as a final product, a single-line diagram of the complete project is to be presented. From the complete diagram, it can be inferred how the plant is connected to the pre-existing plant in Turbigo. During the project development, it was decided to use the AutoCAD software instead of the company's Integra software, since the latter presented some issues in representing bidirectional loads such as batteries.

The complete diagram starts from the high-voltage access point to the 6kV medium-voltage switchboard and includes all the downstream components of the panel: it comprehend the 5 subsystems of the existing plant in Turbigo, highlighted with red labels, and the new plant designed in this thesis, indicated with green text. In figure 61 it is shown the complete electrical scheme prodyced but given its exstension in order to be clearly readable, the complete project will be printed in a very large on paper format A1 .In this section only some details will be shown to explain the logic of the diagram.

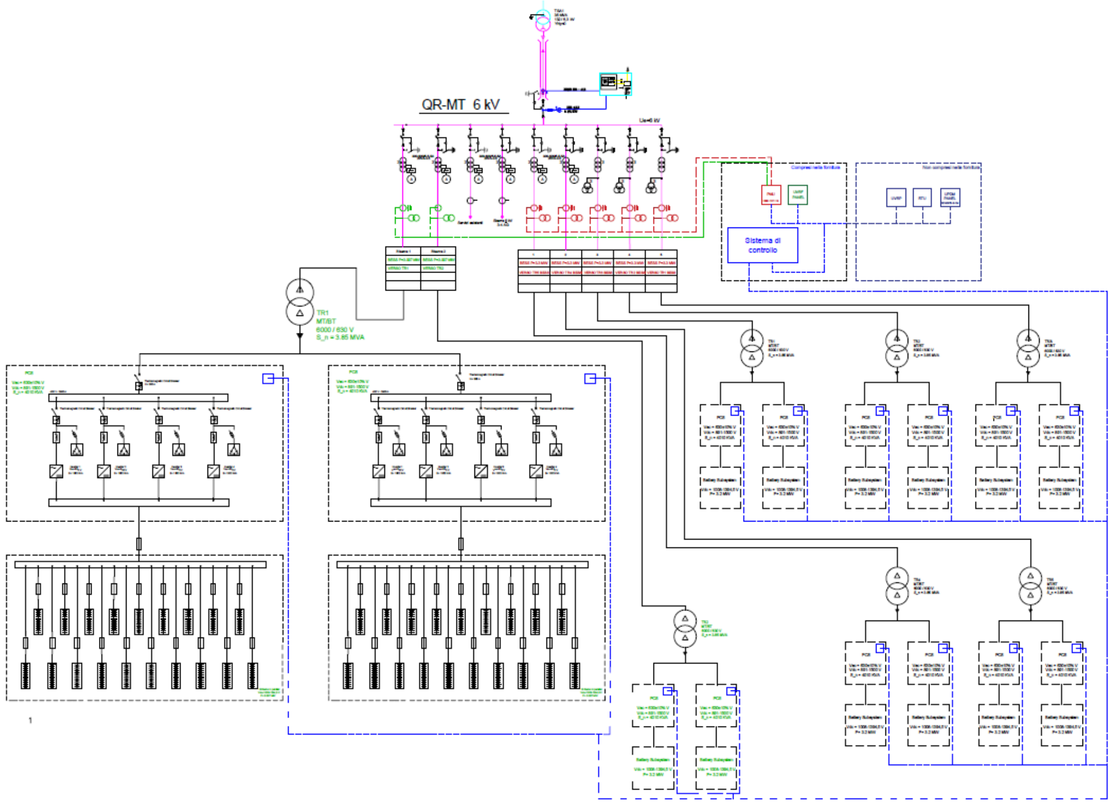

Figure 61: Detail of the part of the system studied for this thesis; more details can be found in the attached table

In Figure 62, a detail of how the BESS system is represented is shown, while in picture 63 is rappresented the second subsystem, rappresented without details in order to save space on the print.

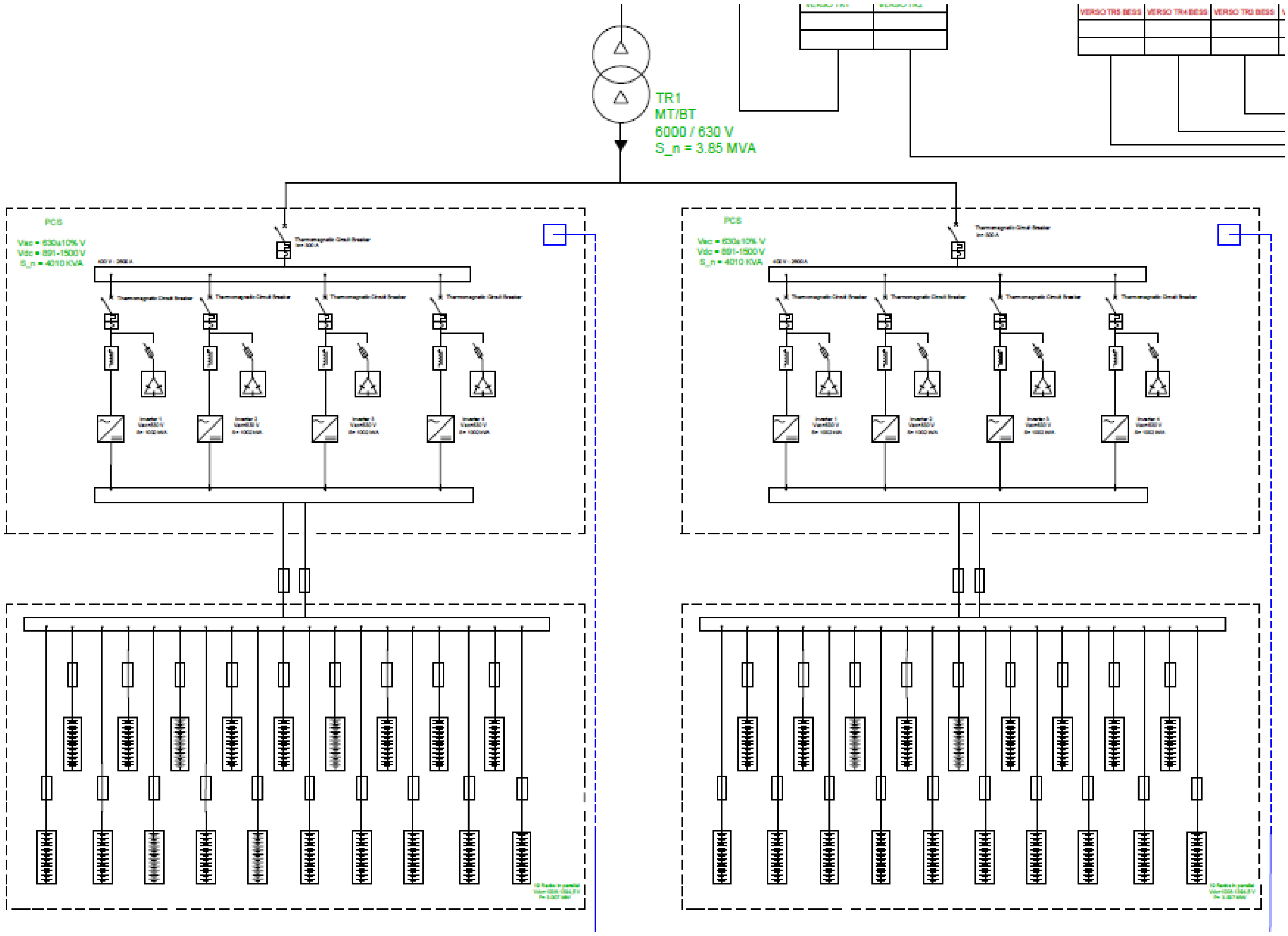

Figure 62: A BESS complete subsystem

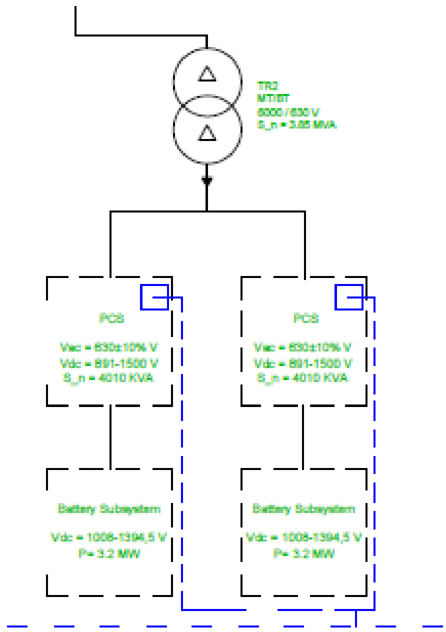

Figure 63: Simplified subsystem as shown earlier

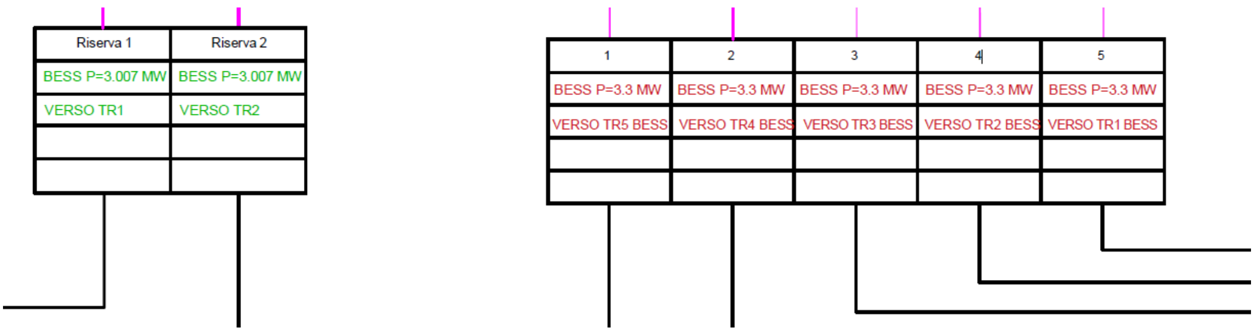

Figure 64: Description of the starts from the MV switch-box

In Figure 64, the 7 feeders from the medium-voltage switchboard can be seen: two in green for the new plant, while five in red for the previous BESS. Colors were also used as an aid to understanding the diagram: in blue and dashed lines all the signal and control data necessary for the control system to command and interact with the batteries are fed back to the Control Block, also represented in blue.

4 Conclusions

From this work, it is clear that IREN Energia is seizing the opportunities offered by technological innovation in the energy sector. In particular, the pilot project developed in recent years has enabled the company to verify the concrete advantages of integrating Battery Energy Storage Systems (BESS) to support existing thermoelectric power plants. The experience gained has demonstrated not only the technical feasibility of the solution but also its economic and managerial effectiveness, to the point of steering corporate strategy toward further developments in this direction.

This orientation is fully aligned with broader national and international perspectives, which envision the electrical system moving decisively toward a bidirectional, resilient, and reliable grid, capable of ensuring both security of supply and high standards of environmental sustainability. Energy storage is, in fact, a fundamental element of the ongoing transition, as it enables the compensation of renewable variability while improving the overall quality of the energy delivered to the grid. In this context, IREN Energia's commitment is not simply a matter of internal strategy, but rather a contribution to a wider systemic vision that concerns the entire Italian electricity sector.

At the same time, the evolution of economic and regulatory reforms governing the ancillary services market opens up particularly promising prospects. The progressive introduction of more competitive and transparent mechanisms is creating favorable conditions for storage systems to generate increasing profits in the years ahead. The ability of BESS to provide services such as frequency regulation, voltage stabilization, and reserve power makes them essential assets whose profitability is likely to grow as the demand for these services expands. In this respect, IREN Energia's pioneering role allows it to gain a strategic advantage over other operators who may enter the market at a later stage.

With appropriate periodic maintenance, the plants analyzed and designed within this thesis are expected to guarantee a long operational lifetime while ensuring stable revenues. The benefits arise not only from the successful participation in ancillary service auctions but also from the improved quality of the energy supplied. By reducing fluctuations and increasing continuity, these plants significantly lower the risk of incurring penalties and sanctions, which often burden conventional power stations when energy quality standards are not met.

Another relevant aspect is the ease with which the new installation can be integrated into the existing infrastructure at Turbigo. The design process deliberately favored solutions consistent with what is already in place, thus minimizing the need for additional staff training and reducing the likelihood of complications during installation. This pragmatic approach suggests that the implementation process will be straightforward, free of major obstacles, and more cost-effective overall.

The construction of the facility discussed in this study is scheduled for 2026, wuth the hope that time storage technologies will be even more established and widely recognized as indispensable components of the European energy landscape. It is intended that this thesis may serve as a reference framework for the definition of the final project that the company itself will carry forward. In this sense, the work presented here should not be considered merely as a snapshot of the current state of the art, but rather as a design blueprint, capable of guiding future decisions and consolidating the path already undertaken.

In conclusion, the project analyzed represents a clear example of how it is possible to combine technical efficiency, economic sustainability, and environmental objectives. Thanks to the expertise acquired and the strategic vision demonstrated, IREN Energia positions itself as a key player within the national energy transition. The integration of BESS does not merely provide an immediate competitive advantage but also constitutes an investment in the future, fully aligned with the broader need to evolve toward a more modern, flexible, and sustainable electrical system.

Ringraziamenti

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