# INTEGRATED THERMAL ENERGY STORAGE SYSTEM – ROLE OF MANAGEMENT STRATEGY IN DESIGN OF A STORAGE TANK

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## ABSTRACT

In recent years, our society has experienced an important energy transition that is becoming a central aspect in geopolitical choices in several countries around the world. However, several issues arise from these scenarios, in which an increasing number of RES power plants are installed and connected to electrical grids. In fact, most renewable sources, such as wind and solar, are characterised by a fluctuating and unpredictable behaviour that causes a decrease in the quality of the energy transmitted through the grid and leads to a more difficult management of the grid itself. To mitigate and reduce these negative aspects, it is important to install devices, such as storage systems, capable of facilitating the correct management of electrical grids, meeting, at the same time, the electrical demand of the users and the energy produced in RES-based power plants. Although several technologies have been proposed over the years, Carnot batteries seem to guarantee adequate performances without stringent geographical constraints and represent a promising solution. Among them, integrated thermal energy storage systems (IT-ESS) can be easily installed and coupled with existing power plants. The central element of such technology is represented by a sensible heat-thermal energy storage device, consisting of a packed bed. The literature is still lacking accurate design methods for the storage tank, and this is the leading aspect that led the authors to develop an innovative procedure to determine the size of the storage device, based on the necessity of producing energy during the night, while the accumulation phase occurs during the day. In this phase, the power of a photovoltaic plant is exploited: the plant is described through curves that reproduce the power generated in a typical day for each month of the year. An algorithm built in the MATLAB environment had been used to determine the volume of the storage device, with the goal of being able to cover the hours in which the PV is not producing energy. The results of the analysis have underlined the need to consider in a proper way both the user needs and the characteristics of the renewable power plants, to correctly evaluate the volume of the storage tank to be installed in the system.

## 1 INTRODUCTION

In recent years, our society has been promoting renewable energy sources (RES) to reduce pollutants and carbon dioxide emissions. According to the Electricity Market Report 2023 (International Energy Agency, 2023a), among the most impactful sectors, electricity generation is responsible for approximately 13.2 Gt of $CO_2$. Consequently, there is a need to replace traditional fossil fuels with renewable sources, such as solar or wind, to move toward the decarbonisation of the most impacting sectors and, at the same time, promote a more responsible use of energy sources. Consequently, in several countries, new policies are introduced to promote the integration of renewable sources into their actual energy mix. Various international organisations highlighted that in the next years the renewable installations will increase: the Renewables 2023 report (International Energy Agency, 2024) states that the 2023 annual global renewable power additions increased to about 510 GW, 50% more with respect to 2022. This is considered the fastest growth of renewable sources in the last two decades and is mainly due to continuous policy support in several countries. It is expected to see another increase in the next years, in particular for wind and photovoltaic technologies. In 2022, these two energy sources are forecast to increase more than double before 2028, reaching almost 710 GW. Furthermore, in 2028, the potential generation of renewable energy is expected to increase by about 70% with respect to 2022,



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reaching around 14400 TWh. Similar data and expected trends are reported in the World Energy Outlook 2023 (International Energy Agency, 2023b). In addition to policy support, the reduction in the costs of renewable technologies and the variability of electricity and gas prices in recent years, mainly related to recent geopolitical crises, represent other aspects that allow for a further development and installation of renewable energy sources.

Even if the integration of renewable systems is extremely important in reducing pollutants and emissions, high penetration of renewables results in significant challenges in maintaining the frequency of the electrical grid and the quality of energy transmitted within the prescribed limits (Saha et al., 2023). Moreover, renewable sources, such as wind or solar, are characterised by an unpredictable and variable behaviour strongly dependent on the meteorological conditions that increases the difficulty in the forecast of demand and production curves for the electricity market: in particular, these sources increase the mismatches between energy supply and demand. Therefore, it is necessary to install and develop new solutions that can mitigate these negative effects (Dalala et al., 2022). Energy storage systems represent a possible solution to reduce these mismatches between energy production from renewable sources and user demand (Beaudin et al., 2010; Cárdenas et al., 2021), allowing mitigation of issues derived from high renewable penetration.

Over the years, several innovative technologies have been proposed and investigated in the field of energy storage. Among the large-scale technologies, the most interesting solutions are represented by Compressed Air Energy Storage Systems (CAES), Flow Batteries (FB), and the so-called Pumped Hydro systems (PHS): these are the most mature and commercially available technologies. However, each of these solutions is characterised by some negative aspects that underline the requirement of developing new technologies. For example, CAES systems suffer from high investment costs and require stringent geographic and morphological constraints. Moreover, some fossil fuel streams are generally required for their proper functioning (Budt et al., 2016; Venkataramani et al., 2016). More in detail, the energy density can vary between 3 and 12 Wh/l, the round-trip efficiency ranges between 40% and 95%, while the price is expected in the range of 2-200 $/kWh. The useful life of this technology is expected to be very long (20-60 years) (Benato and Stoppato, 2018a). Flow batteries are a relatively new technology that functions in a similar way to traditional electrical batteries. The investment costs are high (the price per energy unit stored is 120-1000 $/kWh), and this technology is also characterised by a poor lifetime (5 to 15 years). Energy density spaces in the range 16-60 Wh/l and the round-trip efficiency is between 57% and 90% (Benato and Stoppato, 2018a; Divya and stergaard, 2009). For what regards pumped hydro storage, the high investment costs are associated with the necessity of realising important building works, such as dims and penstocks, and there are various morphological constraints that increase the difficulties in spreading this technology: there is the need of a sufficiently high difference in altitude in the water basins and an almost constant mass flow rate. In addition, the energy density associated to PHS is pretty low, and assumes values comprise between 0.5-1.5 Wh/l or 0.5-1.5 Wh/kg. The positive aspects of this technology are associated with a low self-discharge rate (in the range of 0.005-0.02 %), a high round-trip efficiency (65-78%), and a long life that can vary between 30 and 60 years (Barbour et al., 2016; Deane et al., 2010; Rehman et al., 2015; Steffen, 2012).

We can clearly understand that a further and faster improvement and development of these technologies is precluded by the above-mentioned aspects. Therefore, it is mandatory to investigate new solutions that are reliable and capable of addressing the negative aspects of high penetration of renewables. In the last few years, the research primarily focused on thermomechanical storage solutions, among which the so-called Carnot Batteries (CB) represent a valid and promising alternative to traditional storage technologies (Dumont et al., 2020; Vecchi et al., 2022). In general terms, when describing the functioning of Carnot batteries, it is possible to distinguish between two different processes, generally indicated as the charging and discharging phases. During the charge, electricity is transformed into heat, which is subsequently stored as thermal energy in the storage material, while in the discharge process, the previously stored heat is converted back into electricity and delivered to the electrical grid.

Over the years, different types of CBs have been introduced and studied (Benato and Stoppato, 2018a; Dumont et al., 2020): It is possible to consider sensible or latent thermal energy storages (TES) or different discharging processes (Rankine, Brayton-Joule, Kalina). Even if there are various possible configurations, the most studied are the Pumped Thermal Energy Storage (PTES) systems, characterised by high energy density, low self-discharge rates, small installation footprints, and do not



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require geographical or morphological constraints. PTES systems are based on a high-temperature heat pump cycle, which allows the conversion of off-peak electricity into heat, stored in two manufactured vessels exploiting suitable storage media. During the discharge phase, which usually occurs when there is a high electricity demand from the grid, the system exploits a thermal engine cycle. The adopted working fluid is a gaseous medium such as argon or, more frequently, the external ambient air. For storage, economic solid materials are used, such as concrete, common minerals, or gravel and stones. Moreover, this kind of system is suitable for exploiting the components of existing out-of-market fossil-based thermal power plants.

From the idea of PTES systems, the authors investigated and developed a storage device named Integrated Thermal Energy Storage (I-ESS) (Benato et al., 2022; Benato and Stoppato, 2019, 2018b). In short, the plant stores electricity by converting it into sensible heat within a high-temperature artificial tank equipped with a packed bed. The I-ESS plant operates as an open cycle, exploiting air as the working fluid during both the charging and discharging phases. During discharging, the power train functions as a gas turbine, with the high-temperature tank serving as a replacement for the combustion chamber. This technology does not require morphological constraints and is characterised by a good lifespan and low-complex layouts.

Even if the potentialities of this storage technology are evident, in literature it is difficult to find a well-defined procedure that allows to evaluate the proper volume of the storage device. Thus, the authors tried to investigate how to determine the volume of the storage system, accounting for the user needs. In fact, it is fundamental to consider that user needs must be placed at the centre of the analysis: Different users require different storage system management strategies. Consequently, the design of such systems is based on the analysis of the user and is based on its specific requirements. Before going into detail about the procedures and methods adopted, it is important to first focus on the I-ESS technology to properly understand its functioning. In the following sections, we will also analyse the model used to describe the behaviour of the storage device.

## 2 THE INTEGRATED ENERGY STORAGE SYSTEM

As seen previously, there is an urgent need to develop and introduce innovative solutions in the energy storage sector, capable of mitigating the penetration of renewable energy and preserving the proper functioning of the electrical grid. Furthermore, the possibility of exploiting devices already present in decommissioning power plants has led the authors to propose and investigate the Integrated Energy Storage System (I-ESS) (Benato et al., 2022; Benato and Stoppato, 2019, 2018b). The general idea behind the proposed system is that when the production from renewable sources, such as solar or wind, is high and, at the same time, the energy required by the users is low, the surplus of electricity can be converted into heat through an electric heater and stored in the high-temperature sensible heat storage unit consisting of a packed bed. During peak hours, during which the energy demanded by users is high, a modified air bottoming cycle unit is used to generate electricity exploiting the previously stored thermal energy.

In Figure 1, the schemes for the charging and for the discharging processes are reported.

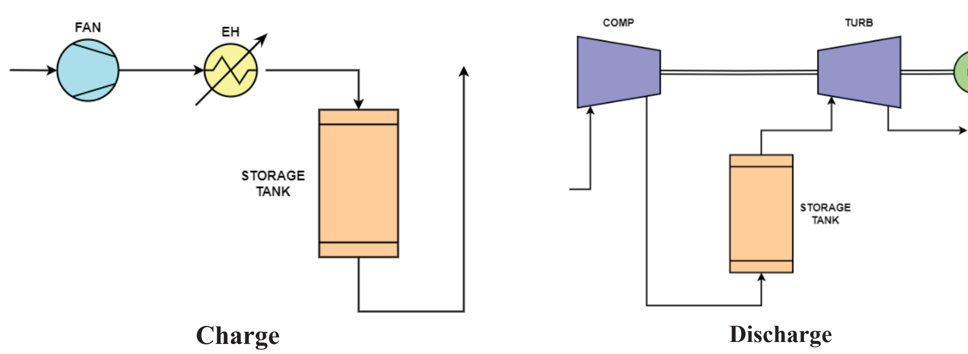


**Figure 1**: Schemes of the proposed system.


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As previously seen, we can distinguish between a charging process, in which thermal energy is stored in a manufactured storage tank, and a discharge phase, characterised by electricity generation exploiting the previously stored heat.
More in detail, the charge consists of an open cycle in which the external air is drawn out of the environment through a blower or a fan (FAN) and sent through an electric heater (EH) able to increase its temperature up to the desired value. At this point, hot air is forced to pass through the storage tank, which consists of a packed bed, in which the working fluid releases its heat to the storage material. Consequently, the temperature of the storage material slowly increases with the proceeding of the charge. Once it passes through the storage tank, the air is released into the external environment. The adoption of an electric heater enables maintaining the storage tank inlet temperature during the charge at a constant value, independently of the ambient air conditions. Moreover, through this configuration it is possible to use a blower characterised by a pressure ratio sufficient to cover just the pressure losses in the circuit, instead of a compressor with a high-pressure ratio, present in the traditional PTES arrangements. This aspect is extremely important as it leads to a reduction of the complexity of the machinery required for the charging process.
When the discharge process occurs, the system operates according to a Brayton-Joule cycle, modified by substituting the combustion chamber with the storage tank: first, the ambient air is compressed through a compressor (COMP); then it is sent in the storage tank to be heated up. Lastly, high-pressure and temperature air is delivered to a turbine (TURB), mechanically coupled with an electric generator (MG).
A slightly modified configuration, in which a regenerative heat exchanger is introduced, both during the charging and the discharging phases, can be adopted as well. This device, inserted after the blower and the compressor in the charge and the discharge, respectively, allows one to recover the energy content in the air at the outlet of the system, if its temperature is sufficiently high. For simplicity, in this work we considered the basic configuration without the heat exchanger.
The arrangement of the storage tank is reported in Figure 2. The device is a vertically structured cylinder with the aim of preventing buoyancy-driven instabilities of the thermal front. The shape of the vessel is cylindrical and is made up of an upper and a lower plenum and the packed bed.
The energy is stored in form of sensible heat in the packed bed, realised with cheap, nontoxic, and nonflammable materials, such as aluminium oxide, concrete, masonry, sand limestone or titanium oxide. In this work, the material considered for the storage tank is aluminium oxide in the form of spheres, randomly displaced in the tank. During the charging process, the air enters the storage tank from the top, while the flow is reversed during the discharge.

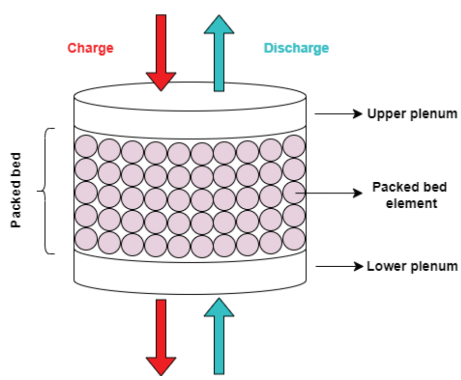


**Figure 2**: Configuration of the storage tank.

Compared to traditional PTES layouts, the arrangement proposed by Benato et al. (Benato et al., 2022; Benato and Stoppato, 2019, 2018b), is less complex and characterised by a lower number of components. Furthermore, the possibility of working with air and nontoxic and nonflammable materials improves the safety of these systems.



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### 2.1 The numerical model of the I-ESS

The numerical model adopted for the description of the I-ESS has been developed by the authors' research group (Benato et al., 2021) (TES-PD model). This model is developed starting from the most important models proposed in the past and available in literature, such as the one of Howell et al. (Howell, 1982), the one described by McTigue et al. (McTigue et al., 2015), or the one of Desrues et al. (Desrues et al., 2010).

More in detail, the TES-PD model describes the storage tank through a set of partial differential equations (ODE), consisting of the conservation of the mass of the fluid (Equation 1), the energy conservation equation for the fluid (Equation 2) and the energy conservation equation for the solid storage material (Equation 3).

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial(\rho_f \cdot v_f)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho_f \cdot T_f)}{\partial t} + \frac{\partial(\rho_f \cdot T_f \cdot v_f)}{\partial x} = \frac{1}{\varepsilon} \cdot \alpha \cdot (T_s - T_f) \tag{2}$$

$$\frac{\partial(\rho_s \cdot c_{p,s} \cdot T_s)}{\partial t} + \frac{\partial}{\partial x}\left(k_{s,eff} \cdot \frac{\partial T_s}{\partial x}\right) = \frac{c_{p,f}}{1-\varepsilon} \cdot \alpha \cdot (T_f - T_s) - U_i \cdot \frac{C_u}{1-\varepsilon} \cdot (T_s - T_{amb}) \tag{3}$$

The set of equations also comprises the one describing the pressure drops (Equation 4) and the equation of state for an ideal gas (Equation 5).

$$\frac{\partial p}{\partial x} = -C_f \cdot \beta \cdot \frac{1}{2} \cdot \rho_f \cdot v_f^2 \tag{4}$$

$$p = \rho_f \cdot r \cdot T_f \tag{5}$$

In the previous expressions, $x$ represents the axial tank coordinate, while $t$ is the time. The properties of the fluid are indicated with the subscript *f*: thus, $\rho_f$ is its density, $v_f$ represents its velocity, $T_f$ is the temperature. Furthermore, the thermodynamic pressure of the fluid is indicated through the symbol $p$. The parameters that denote the temperature and the density of the storage material are $T_s$ and $\rho_s$ respectively. The effective solid thermal conductivity is indicated with $k_{s,eff}$, while the fluid's one is reported as $k_f$. The specific heats at constant pressure are indicated as $c_{p,s}$ for the solid and as $c_{p,f}$ for the fluid, respectively. The parameter $\varepsilon$ is used to denote the void fraction of the packed bed. The ambient temperature is $T_{amb}$ and the specific constant of the gas is $r$. $U_i$ represents the overall thermal transmittance of the tank. The coefficient indicated by the letter $\alpha$, assumes different values according to the geometry of the storage device. In the case of a randomly packed bed of spheres it is possible to calculate it adopting the following Equation 6:

$$\alpha = \frac{6 \cdot Nu \cdot k_f}{c_{p,f} \cdot d^2} \tag{6}$$

Here, $Nu$ is the Nusselt number and $d$ is the equivalent diameter of the particles that make up the bed. The coefficient $\beta$ is calculated according to Equation 7, valid for a packed bed made of spheres:

$$\beta = \frac{1-\varepsilon}{d \cdot \varepsilon} \tag{7}$$

Also, the parameter $C_u$ is related to the geometry of the packed bed. For a bed of randomly packed spheres, it can be determined according to Equation 8:


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$$C_u = \frac{2 \cdot \pi}{A} \cdot \sqrt{\frac{A}{\pi}} \tag{8}$$

The parameter $A$ is the base area of the storage device. The height of the storage itself can be indicated by the letter $L$. The friction factor $C_f$, is obtained through the Ergun equation as reported in (Hicks, 1970) and in Equation 9.

$$C_f = 2 \cdot \left(\frac{150}{Re_h} + 1.75\right) \tag{9}$$

$Re_h$ is the hydraulic Reynolds number, computed as reported in the following Equation 10, starting from the $Re$ number and the void fraction:

$$Re_h = \frac{1}{1-\varepsilon} \cdot Re \tag{10}$$

In particular, the TES-PD model relies on the model formulated by Desrues et al. (Desrues et al., 2010), but the authors modified it by adding a set of parameters able to better describe the behaviour of the storage tank: first of all, they accounted for the time and space variability of the properties of both the fluid and the storage material, focussing in particular on the solid material effective thermal conductivity. Lastly, they implemented the overall heat loss coefficient. In fact, the model proposed by Desrues et al. (Desrues et al., 2010) even if it can be considered as one of the most advanced formulations able to describe the storage device, does not account for the variability of the solid and fluid properties, which are assumed constant and calculated at a reference temperature. In the TES-PD model, the properties are evaluated from the National Institute of Standards and Technology (NIST database) and exploiting the RefProp database. For what concerns the heat losses, they are accounted only in the model proposed by Howell et al. (Howell, 1982): this parameter is of extremely importance in order to evaluate in the proper way the behaviour of the storage tank for long simulations.

## 3 THE VIRTUAL POWER PLANT AND THE MANAGEMENT STRATEGY

In this paper, a case study is presented based on a PV plant. The photovoltaic facility is characterised by a peak power of 10.316 $MW_p$ and is in Portoscuro, Sardinia; the panels are orientated by 32 °. The annual mean energy output is equal to 16 GWh. To characterise the production of the plant, it was considered to individuate a typical daily profile for each month, evaluating the power produced by the photovoltaic field every 15 minutes. Consequently, 12 curves are obtained, each characteristic of a month of the year (Figure 3). Moreover, it was considered to maintain this average profile for each day of the month.

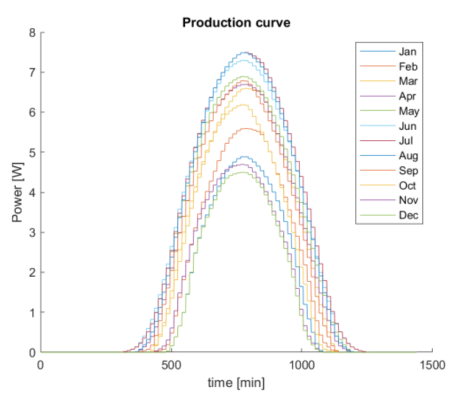


**Figure 3**: Power production curves for each month of a year.



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To evaluate the management strategy of the storage system and its proper functioning, it is important to define the various interconnections between storage and the other actors that participate in the production of energy. Therefore, the entire system can be treated as a virtual power plant (VPP). This innovative concept can be defined as a "cloud-based platform that aggregates distributed energy sources, loads of various nature, storages and electric vehicles, providing real-time monitoring via a bidirectional communication system, aims to establish a distributed and decentralised power plant enhancing energy management and trading across the power system" (Rouzbahani et al., 2021). A VPP can consist of a series of distributed users (loads), generators, storage systems, and other devices and technologies (Zhou et al., 2016) that lead to the improvement of the efficiency and the management of the energy exchanges between the various entities that constitute the system (Benato et al., 2022). In the case under analysis, the storage is connected to a photovoltaic (PV) plant and to the electrical grid. Similarly, the PV plant is connected to the electrical grid: In this way, the electricity produced in the PV facility can be directly injected into the grid or can be sent to the IESS to be accumulated. Moreover, to allow the IESS and its associated components to start, a battery park is included in the VPP and acts as a backup system. In the simulations performed in the study it is not considered, seen its marginal role in the configuration adopted. The VPP scheme is reported in Figure 4.

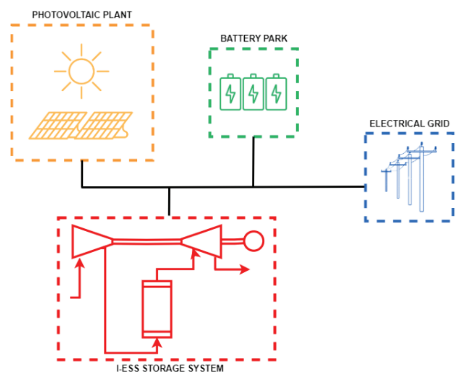


**Figure 4: The** scheme of the VPP as intended in (Benato et al., 2022).

The management of the VPP is based on the possibility of accumulating the energy produced in the PV plant, and not required immediately by the users and the grid, in IESS. During the night or when the energy demand is high, the IESS delivers the previously accumulated energy performing the discharging phase. The electricity produced by the plant in this phase is delivered to the electrical grid to meet the needs of users. To perform an analysis aimed at defining the proper management strategy of the storage system and individuating the dimensions of the storage device implemented in the system, both economic and technical aspects must be considered.

To define a suitable management strategy for the plant, it was decided to use the storage system to accumulate energy during the day, following the power production curve of the photovoltaic facility. Then, the previously accumulated energy is used to produce electricity during the night, with constant power. More in detail, during the charging process, we can consider following the PV plant power production curve and assume that the instantaneous power coincides with the power required by the blower and the electric heater. In this way, the charging process is performed by varying the mass flow rate. The blower is characterised by a maximum and a minimum allowable values of mass flow rate that can be processed: These two values represent the limits for the maximum and the minimum power absorbed by the machines. In this way, we can store all the energy produced by the photovoltaic plant as thermal energy in the storage tank. During discharge, the authors decided to perform an analysis in which the mass flow rate is maintained constant for the entire process.

For proper system management, the durations of charge and discharge are extremely important. First, it is necessary to define when the charging and discharging phases can be considered completed. For this purpose, it was decided to analyse the temperature of the air that exits the storage tank in both processes: during charge, when the temperature of the air increases above a certain limit value (set equal


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to 950 °C) the process finishes; similarly, for discharge, if the temperature of the air at the exit of the storage tank and thus at the input of the gas turbine decreases below a limit value (set at 800 °C), the process is stopped. Consequently, the duration of the charging process corresponds to the number of hours in which the PV plant generates a power able to feed the blower and the electric heater, while the duration of the discharge is the number of hours in which the production is not sufficient to feed the two devices and when the PV plant is not generating at all (e. g. during the night).

The storage must have a volume that makes it capable of producing energy for the entire duration of the discharge phase, starting from the fully charged tank, even in case the worst situation occurs in which it is required to generate electricity for all hours in which the production is null. Anyway, when the system is operated, the user could be interested in producing energy just when the energy is characterised by a higher price. Thus, storage can be managed to generate energy for a lower number of hours. Of course, if the user is interested in covering the hours with a null energy production, he/she can manage the storage to perform a complete charge before starting the discharge process.

In the case here presented and analysed, it was decided to fully charge the storage tank, starting with the tank at ambient conditions, and to individuate the volume that allows performing a complete discharging process able to cover all the hours in which the production of the PV plant is null or not sufficient to feed the blower and the electric heater. During the charging process, it is assumed that the power absorbed by the electric heater and the blower is equal to the power generated by the photovoltaic plant multiplied by a certain value of electrical efficiency of the electric motor of the blower and the electric heater. In Figure 5 is reported the algorithm scheme implemented in MatLab environment to individualise the volume for the storage device. In this paper, the months characterised by the highest and the lowest energy production, which are July and December, respectively, are analysed. In Table 1, the main parameters of the storage systems are reported. The maximum temperature is chosen considering the technical limits imposed by the material considered for the packed bed (aluminium oxide). For the number of subdivisions of the tank $N$ the authors adopted a value able to guarantee a fast simulation but sufficiently accurate in describing the behavior of the storage device. In Table 2, other characteristic parameters of the turbomachinery are reported.

**Table 1**: Storage tank parameter.

| **Parameter** | **Symbol** | **Value** |
|---|---|---|
| Maximum temperature | $T_{max}$ [° C] | 1000 |
| Density of the storage material | $\rho_s$ [kg/m$^3$] | 3990 |
| Tank thermal transmittance | $U_i$ [W/(m$^2$ K)] | 0.7 |
| Void fraction | $\varepsilon$ [-] | 0.4 |
| Diameter of Bed Particles | $d$ [m] | $50 \cdot 10^{-3}$ |
| Number of layers | $N$ [-] | 60 |

**Table 2**: Parameters involved in the simulations.

| **Parameter** | **Unit** | **Value** |
|---|---|---|
| Polytropic efficiency of turbomachinery | [%] | 85 |
| Blower pressure ratio | [-] | 1.5 |
| Compressor pressure ratio | [-] | 8 |
| Electrical efficiency of turbomachinery | [%] | 98 |
| Electrical efficiency of an electric heater | [%] | 98 |
| Design mass flow rate of the blower | [kg/s] | 5 |
| Design mass flow rate of the compressor | [kg/s] | 3.4 |



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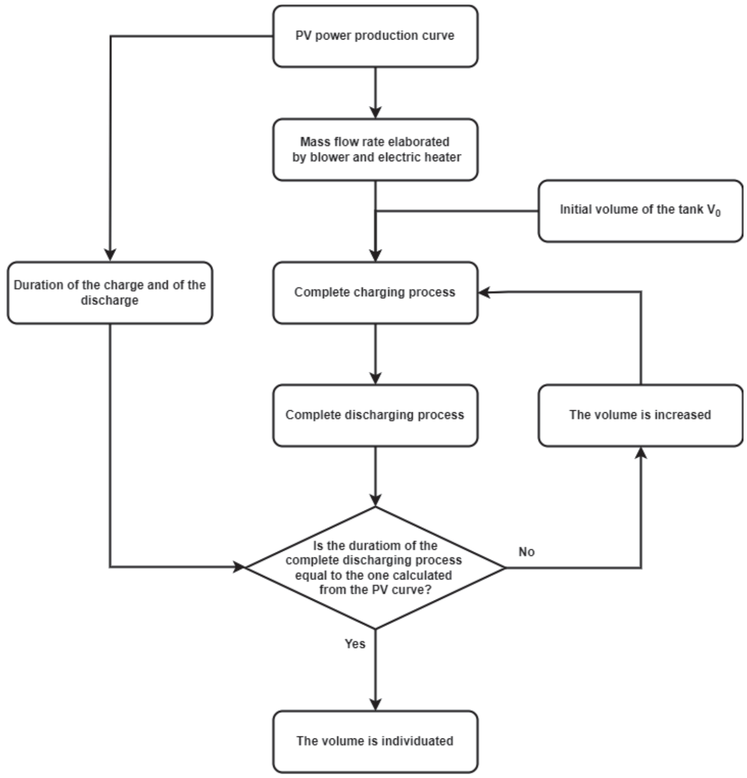


**Figure 4**: Flowchart illustrating the algorithm implemented.

## 4 RESULTS AND DISCUSSION

The results of the simulations performed are listed in Table 3 for the months of July and December. In particular, the durations of charge and discharge are reported, as well as the volumes obtained from the simulations: the volume required to completely cover the discharge phase during the month of December is greater than the one obtained for July. This is due to the longer period in which the system is asked to supply energy during December. To understand the meaning of the parameter denoted 'duration complete charge', it is necessary to understand that the time required to completely charge the storage device strongly depends on the initial state of charge of the tank itself. For the first charging process, the initial state is a tank at uniform ambient temperature, but for the second charging phase this initial condition cannot be reached, since it is not possible to perform a discharge process capable of completely extracting all the energy previously accumulated due to the limits imposed for the correct functioning of the turbomachines. Thus, this parameter represents the time required to complete the accumulation, starting from the temperature stratification obtained when we extract all the allowable energy from the storage.

**Table 3**: Results of the simulations.

| **July** | | **December** | |
|---|---|---|---|
| Duration charge [min] | 585 | Duration charge [min] | 375 |
| Duration discharge [min] | 855 | Duration discharge [min] | 1065 |
| Duration complete charge [min] | 885 | Duration complete charge [min] | 1517 |
| Volume [$m^3$] | 78 | Volume [$m^3$] | 98 |
| Height of the tank [m] | 3 | Height of the tank [m] | 3 |
| Efficiency [%] | 13.7 | Efficiency [%] | 13.9 |


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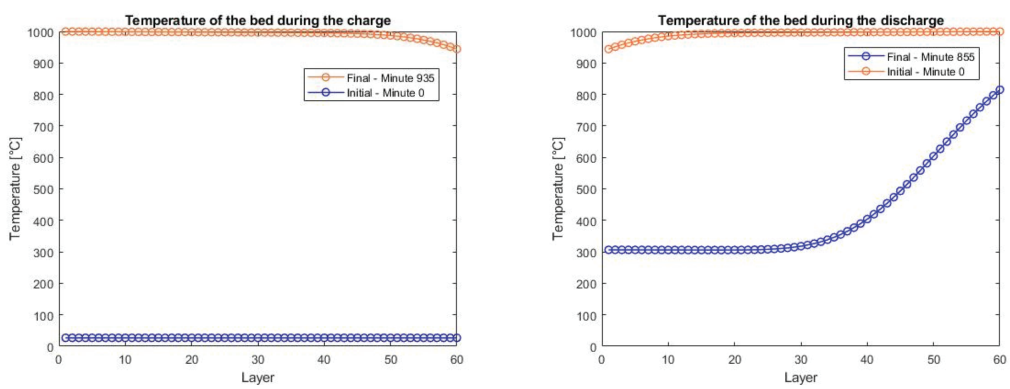
The efficiency reported in Table 3, has been calculated as the ratio between the energy obtained during a complete discharge phase and the energy accumulated starting from the tank at a uniform ambient temperature. This parameter is not properly the round trip efficiency that is usually defined while dealing with storage technologies, since it is generally computed considering to achieve, at the end of the discharge, the same condition of the tank at the beginning of the charge: in our case it is not possible to have the same initial temperature distribution in the tank due to the limits imposed by the turbomachines during the discharge. The efficiency is characterised by a low value, and it is strongly affected by the temperature limit for which the charging process is assumed to be completed: in fact, heating the last layers of the tank to the desired temperature requires a lot of energy, and the air exiting the storage close to the end of the phase is characterised by a high temperature. To improve the efficiency, it is possible to include an internal heat exchanger or exploit the high-temperature air streams to produce useful heat if required by the user.

To better understand the state of charge of the tank, in Figure 6, the temperature profiles of the packed bed for the first charge and the discharge processes are reported for the month of July. In both diagrams, it is possible to distinguish the initial profile from the final one. For the charge, we can clearly see that at the beginning of the simulation, the entire tank is at the same ambient temperature; at the end of the charging process, we can see that most of the layers have achieved a temperature close to the maximum one. The last layers met by the air are characterised by a lower temperature: this is because the charging process is considered completed when the air exiting the storage tank reaches the limit temperature, that is, lower with respect to the maximum temperature. For the discharging process, the air flows in the opposite direction with respect to the charging one: consequently, the first layer encountered by the air during the charge becomes the last layer during the discharging process and vice versa. On observing the graph describing the temperature distribution during the discharging, we can see that the profile at the beginning of the process coincides with the one achieved at the end of the charging process. The final temperature profile corresponds to the end of the discharging process: we can see that the first layers have reached a lover temperature (approximately 300 °C) that is close to the air temperature at the outlet of the compressor.




**Charge** **Discharge**

**Figure 5**: Temperature profiles of the packed bed.

In Figure 7 are reported the temperature profiles of a charging process that begins with the tank not in an isothermal condition with a temperature equal to the external one. In particular, the starting temperature profile is the one achieved after the first discharging process. Figure 7a shows the results obtained from the simulation in which the system had been charged for an entire day: at the end of the simulation, we observe that we are able to store all the energy without reaching the complete charge of the tank. In Figure 7b, we can observe the case in which we are interested in completing the charging process, to have the possibility of covering all hours with null production from the photovoltaic plant. In this case, the temperature profile at the end of the simulation is the same of the one achieved starting the process with the storage tank in isothermal ambient conditions.



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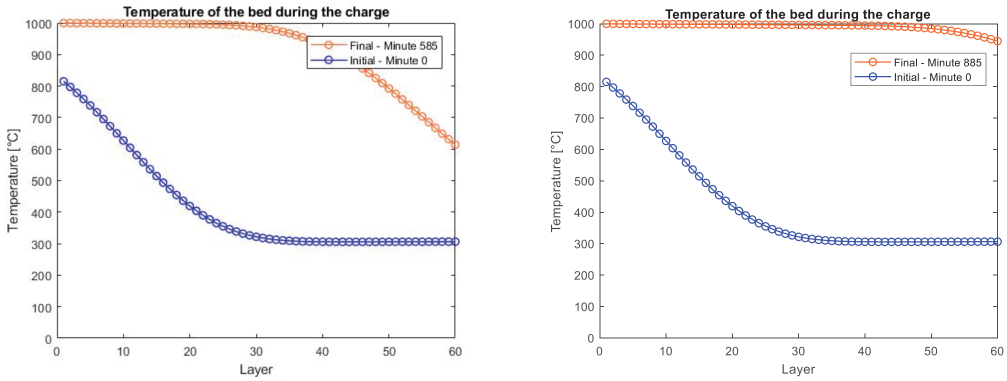


**7a** **7b**

**Figure 6**: Temperature profile for a charge with the tank in a non-isothermal condition.

## 5 CONCLUSIONS AND FUTURE WORKS

In this work, the author investigated a procedure for the management strategy for an I-ESS storage system connected to the electrical grid and to a photovoltaic facility and how it affects the choice of the volume of the storage tank. In the future, the system will be analysed to find the appropriate management solutions and individuating an optimum size of the storage device. Moreover, the main parameters that characterised the storage tank need to be investigated to understand their role in the choice of the volumes: a deep analysis will regard the pressure drops and how they are affected by the height of the packed bed and by the temperature level of the storage tank. Similarly, it will be important to understand the role of the height of the tank on the duration of the charging and discharging processes. Also, different configurations must be studied to understand how to improve the efficiency of the storage system. In future works, a more complex system will be studied in which several generators and users are simultaneously connected to the I-ESS system. The focus will be on investigating the best management strategy, capable of meeting the needs of users, exploring the possibility to supply both electrical and thermal energy. In these scenarios, the electricity market price system will be integrated, to assess the convenience of I-ESS in real-time operations. Similarly, eventual tariff systems and incentives must be taken into account to assess the economic feasibility of I-ESS in a complex high-complex VPP. Moreover, several other management solutions will be investigated, always taking into account users and their needs. In this way, we are going to study the range of applicability of the I-ESS spacing from industrial users to residential ones and from the electrical grid to district heating.

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