

## Research papers

# Demonstration of sector-coupling based on advanced Thermal Energy Storage: a Model Predictive Control framework for load-shifting and grid-balancing

Ilaria Marotta <sup>a,\*</sup>, Yangzhe Chen <sup>b</sup>, Qian Wang <sup>b</sup>, Joel Nadal <sup>c</sup>, David Verez <sup>c</sup>, Fabio Lilliu <sup>d</sup>, Diego Reforgiato Recupero <sup>d,e</sup>, Marco Calderoni <sup>e</sup>, Andrea Frazzica <sup>a</sup>, Valeria Palomba <sup>a</sup>

<sup>a</sup> National Research Council (CNR) of Italy, Institute for Advanced Energy Technologies (CNR-ITAE), 98126 Messina, Italy

<sup>b</sup> Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm 100 44, Sweden

<sup>c</sup> Armengol & Ros Consultors i Associats SL, 08003 Barcelona, Spain

<sup>d</sup> University of Cagliari, Department of Mathematics and Computer Science; 09124 Cagliari, Italy

<sup>e</sup> R2M Solution, 27100 Pavia, Italy



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## ABSTRACT

The roadmap for urban sustainability involves the transition to reliable and decarbonised energy networks. In this regard, business concepts based on sector coupling through the use of Thermal Energy Storage (TES) systems can play a key role. This research is placed in this context, with the aim of evaluating the flexibility potential of novel TES in order to provide load shifting services to the electricity grid and improve the renewables penetration. The idea involves the modelling of the TES upscaling scenarios on the national territory and the simulation of energy demand starting from real data on the electricity grid from European TSOs. For this purpose, a Model Predictive Control Framework (MPC) is developed and implemented in Python environment and the results for the case study of Italy are presented. Starting from the time-series data of energy production and consumption at national level, the actual fraction of electricity used for heating and cooling is calculated and the potential of using short-term and mid-term thermal energy storage for minimizing the surplus from renewable energy sources (RES) in the grid is evaluated. As a result, alternative hourly load profiles based on load shifting are proposed and the flexibility potential and sustainability impact of such systems is discussed. The findings show a reduction of 57 % per year of the RES surplus with values close to 100 % during winter days under the considered thermal energy storage capacity scenario. In addition, at least 10 % load shifting potential is achieved. The research provides a contribution to the demonstration and optimization of sector coupling concepts and discusses future outlooks and directions. Lessons learned can constitute insights for policy makers and technology providers, boosting research and diffusion of thermal energy storage technologies as an alternative to batteries and hydrogen systems for unlocking the flexibility potential of electric grids.

## 1. Introduction

The Renewable Energy Sources (RES) penetration in the electrical mix of the European countries is increasing year by year [1,2]. The unpredictable intrinsic characteristic of some RES requires innovative solutions for grid flexibility and energy storage to handle the intermittence. The current tendency in the operation of power systems is evolving from a unidirectional model (centralized generation from power plants to end-users) to an increasing penetration of distributed networks. This shift, marked by the widespread integration of

decentralized, intermittent RES, presents several challenges for grid operators, including reduced power quality (e.g., voltage and frequency fluctuations), increased line loading (congestion, losses), and reduced RES hosting capacity. Smart grid solutions are increasingly recognized as essential for stabilizing and securing network operations while addressing these issues [3,4]. On this line, the integration of energy storage systems within energy infrastructures serves multiple purposes. On the demand side, there is a growing emphasis on enhancing self-consumption and achieving energy balance at the district or micro-grid level [5,6]. This further necessitates storage solutions that align

\* Corresponding author.

E-mail address: [ilaria.marotta@cnr.it](mailto:ilaria.marotta@cnr.it) (I. Marotta).

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energy generation with load demands under highly variable conditions [7,8]. In this context, further research efforts are needed to develop tailored-made Demand Side Management (DSM) approaches, both at the building district scale [9] and the overall energy grid level from the Distribution System Operator (DSO) perspective [10]. DSM includes a plethora of Demand Response and flexibility concepts and refers to strategies aimed at optimizing consumer energy use through efficiency improvements and load shifting [11,12]. Applications include residential energy-saving programs, peak demand reduction, and integration of renewable energy sources by implementing rule-based or data-driven (machine learning) approaches [13,14]. Most of the studies focus on the use of electricity storage batteries and the exploitation of the building thermal mass storage effects [15–17], to improve building flexibility on the one hand, and provide ancillary services to the grid on the other.

Thermal Energy Storage (TES) and Electrical-Thermal Energy Storage (ETES) could be integrated within energy networks and the broader energy system and serve as an innovative resource to enhance the integration of renewable energy grid stability. ETES involves converting electricity directly—such as surplus electricity from renewable sources or to support grid balancing—and subsequently using it for heating or cooling applications [18,19]. TES and ETES can be integrated at various points in the energy system: on the generation side, where they can be paired with energy production systems; within the transmission and distribution networks, including district heating/cooling networks and electricity distribution grids; and on the demand side, where they can directly meet user load requirements [20,21]. Integrating TES with energy generation systems serves various functions based on the type of generation and the management strategies in place. Specifically, TES can enhance production efficiency by creating optimal operating conditions, such as shifting generation from partial to base-load levels, and allow for the decoupling of electricity and heat production, improving demand alignment and optimizing financial returns. Furthermore, the integration of advanced TES within the overall energy system can provide compensation during short outages, particularly beneficial with variable RES, and support Power-to-X operations, facilitating connections between diverse generation systems and energy carriers. Collectively, these functions can increase the grid's RES hosting capacity: during peak renewable output, TES can stabilize the power system by aligning local consumption with RES generation. TES and ETES systems, including those implemented at the building level, contribute to increasing system flexibility, supporting both energy efficiency and human comfort.

Research on the flexibility potential of novel technologies and Thermal Energy Storage (TES) and Electrical-Thermal Energy Storage (ETES) systems is still limited and few studies in the literature have delved into this area. For instance, Bianchi et al. [22] present a control algorithm for solid oxide cells in renewable communities to optimize energy use, while Zhou et al. [23] explore integrating batteries and hydrogen systems to enhance grid stability and energy flexibility. The latter proposes a multi-energy system incorporating district buildings, renewable systems, and hydrogen vehicles to improve self-consumption and mitigate grid dependence. As a result of the Scopus search conducted for this study in January 2025, only 11 studies address TES applications at the building and district scale. Furthermore, research on the topic considers latent and sensible heat storage, whereas the flexibility potential of novel TES, such as Phase Change Materials (PCM) storage devices and Thermochemical Materials Energy Storage (TCM)/sorption technologies has not been explored in depth. As an example, high-density latent heat storage and smart grids are integrated in [24], achieving significant electricity bill savings (of about 20 %) for end-users. Meng et al. [25] introduces a hybrid energy storage system combining TES with power storage (e.g., supercapacitors, lithium batteries) for distributed energy systems. Through optimization, it enhances performance and cost-effectiveness while addressing environmental impacts, applied to a nearly zero-energy community.

Jarvinen et al. [26] highlights the potential of passive thermal energy storage – i.e. thermal mass storage effects of the building envelope - in buildings as a viable energy storage option. It evaluates its performance using conventional metrics and explores commercial opportunities within Australian energy markets. Rotas et al. [27] examines a system integrating renewable technologies (solar thermal, biomass, PVs) with storage solutions (sensible TES, absorption cooling, Li-ion batteries). Simulations show enhanced RES generation, solar contribution, and temporal flexibility, with notable improvements in heating and electricity generation efficiency (24.6 % increase of heating demand covered by solar energy).

On the other hand, no applications on the flexibility and ancillary services offered by TES storage have been explored from the grid side. This gap is further highlighted by the literature review, which primarily focuses on the integration of electrical storage batteries, while the potential of TES or ETES systems as thermal storage solutions to support grid flexibility remains largely unaddressed [28].

Overall, research on the exploitation of electricity storage for grid management combines advanced methodologies and real-world data to analyze innovative solutions for enhancing energy flexibility. In particular, Biancardi et al. [29] delve into the impact of battery storage uptake on the profitability of cross-border interconnectors. The method involves the implementation of data-driven modelling scenarios aimed at assessing changes in transmission capacity and market dynamics across Europe in 2030. The scenarios are exploratory rather than predictive, highlighting how different levels of storage adoption might reshape transmission profitability and cross-border energy flows. It incorporates perspectives from the European Network of Transmission System Operators for Electricity (ENTSO-E), academic studies, and a commercial consultancy, ensuring a comprehensive view of the potential impacts. Maeder et al. [30] introduce FLEXIES, an open-source optimization modelling tool of the electricity network that could be used, in future developments, for the assessment of the potential of demand-side management (DSM) and sector coupling (e.g., Vehicle-to-Grid and power-to-gas technologies). Kies et al. [31] develop a simplified data-driven model of the EU power system based on ENTSO-E data for DSM applications. DSM is modelled as a virtual energy storage equivalent characterized by a time-dependent State of Charge (SoC) and operational constraints. In [32,33] the authors propose strategies to balance the electricity grid with country-level resolution under high solar penetration by leveraging flexible photovoltaic (PV) and wind systems equipped with Battery Energy Storage Systems (BESS). These systems address diurnal imbalances through advanced forecasting, dynamic storage control, and regulation services. Aghdam et al. [34] introduce the concept of Virtual Energy Storage Systems (VESS), integrating diverse technologies such as BESS and common TES systems, and hydrogen storage to address grid congestion and optimize energy market operations. The VESS concept is applied to a multi-carrier system, including electric vehicles and demand response programs, demonstrating its effectiveness in handling extreme load increases. Finally, in Wang et al. [35] the potential of non-residential buildings equipped with grid-responsive HVAC systems to provide ancillary services, such as frequency regulation and spinning reserves, is assessed. These systems can respond within seconds or minutes, making them ideal for smart grids. The study quantifies the capacities of HVAC systems in Hong Kong and identifies methods to overcome challenges.

The literature review here provided underscores a significant research gap in the development of holistic frameworks aimed at managing and optimizing energy flexibility at the building and grid level by using advanced TES storage. Notably, while strategies to couple the electricity and heat sectors are highlighted in numerous energy storage roadmaps, most current applications—across various scales—are predominantly focused on electricity storage and other kind of flexible sources.

### 1.1. Motivation of the research and novelty

As demonstrated by the literature research above, the roadmap for urban sustainability involves the transition to reliable and decarbonised energy networks. Several studies in the last decade stressed the importance of reducing grid congestion and production/dispatchment peaks in the electricity grid, from both an infrastructure perspective and an economic one [36,37]. Strategies commonly employed, as discussed in the state-of-art above, mostly include Demand Side Management options and flexibility in supply-demand balance [38,39]. However, as pointed out also by a recent review [36], the most convenient option when looking at possible methods for reducing grid congestion and increasing the flexibility of resources at national scale is the field of heating and cooling of buildings. In this sense, the studies that are commonly carried out involve the use of power-to-heat technologies in combination with Electrochemical Energy Storage (EES) [30,40,41]. There are only few attempts that aimed to, qualitatively, define the effect of TES at grid scale, but they are only related to the application of large-scale TES in district heating/cooling networks [18,28].

Furthermore, traditional rule-based control strategies often fail to fully exploit the potential of TES due to lack of the ability to anticipate future energy demand, weather conditions, and grid constraints. In contrast, MPC provides an optimization framework for TES operation by forecasting future system states, incorporating constraints, and dynamically adjusting control decisions over a prediction horizon.

Along this line, the current work aims at answering to the question: *“Is it possible to use a combination of short-term and mid-term thermal energy storage capacity to achieve a substantial improvement in the flexibility of the electric grid at national scale to minimize the RES surplus generation?”*

The main outcomes of the research are:

- Development of a Model Predictive Control (MPC) framework to optimize sector-coupling concepts that imply the integration of advanced TES powered by renewable energy in the overall energy system.
- Definition of alternative hourly load profiles based on load shifting from high penalty periods towards low penalty periods, i.e. hours during which there is availability of surplus RES.
- Assessment of the flexibility potential of TES systems and impact on load-shifting and RES penetration in the electricity mix at country level.

### 1.2. Structure of the paper

This paper is structured as follows: [Section 2](#) illustrates the methodology and modelling phases of the research and discusses the main assumptions underlying the analysis. It is divided into two main subsections. [Subsection 2.1](#) describes the input data of the optimization algorithm and the modelling approach used, i.e. data on the electricity generation and load at national scale, thermal energy demand for space heating and cooling and energy conversion factors. On the other hand, [Subsection 2.2](#) provides a detailed description of the mathematical modelling of the optimization problem and the implementation of the overall MPC framework in a Python environment.

[Section 3](#) presents the results of the study and outlines the flexibility potential of advanced TES solutions in terms of load-shifting and optimization of renewable energy penetration. [Section 4](#) focuses on the discussion of the main findings and key insights of the research and highlights future outlooks and, finally, [Section 5](#) presents the conclusions of the study.

## 2. Methodology and main assumptions

The method involves the modelling of the TES upscaling scenarios on the national territory and the simulation of energy demand starting from real data on the electricity mix from European Union (EU) Transmission

System Operators (TSOs) of EU countries. The surplus from RES, available within the national electricity mix, is evaluated and used for the definition of the penalty signal of the flexibility algorithm.

For this purpose, Phase Change Material (PCM)-based TES PCM and Thermochemical (TCM) TES aggregated storages are modelled according to literature and lab data, considering their use as a contribution to the heating and cooling demand of the building stock at national scale. Considering the integration layouts previously discussed, the model foresees the use of two typologies of advanced TES:

- Short-term (daily) TES with PCMs, charged electrically and so in combination with heat pumps;
- Weekly to monthly thermochemical (TCM) sorption storage, charged electrically by means of high temperature heat pumps.

The advanced storage systems are used to store the excess of RES in each hour of the year and subsequently contribute, through discharging, to the space heating and cooling needs of the national building stock.

[Fig. 1](#) presents the flow-chart of the overall methodology. As shown in the Figure, the conceptual approach is structured in five phases briefly described in the following bullet points.

- In phase 1, data time series on actual energy generation and energy consumption at national scale from the ENTSO-E Transparency Platform [42] are analyzed. In this article, the overall flexibility scenario based on a tailor-made MPC algorithm is applied to the Italian case study.
- During phase 2, the hourly data for the whole year and each electrical zone of Italy are re-elaborated and aggregated in Python environment and the RES surplus is evaluated in each time-step.
- In phase 3, the heating and cooling (H&C) demand of the building stock is modelled, starting from the Eurostat data [43,44] and use profiles from the Demand.ninja project [45].
- Phase 4 concerns the modelling of the State of Charge (SoC) of PCM and TCM systems based on literature and lab-testing data.
- Finally, in phase 5, the overall optimization problem is solved in Python environment with the aim of minimizing the RES surplus by means of the optimal integration of advanced TES charging and discharging. As a result, alternative hourly load profiles based on load-shifting are proposed, and the flexibility potential and impact of such systems are highlighted.

[Sub-sections 2.1 and 2.2](#) contain a detailed description of each modelling phase and present the overall problem from a conceptual and mathematical point of view. The overall methodology is graphically shown in [Fig. 1](#).

The main assumptions underlying the research are formulated as follows:

- The flexibility scenario does not take into account potential variations in the electricity mix generation and cross-country trade, as it aims to provide a benchmark of the flexibility potential of the integration of advanced TES based on historical time data series. Furthermore, the electrical assessment of transmission lines, prediction of the grid parameters, such as voltage and frequency, and congestion phenomena is outside the scope of the research.
- The total thermal energy capacity of TES storage is determined based on the data of thermal demand for heating and cooling of the national building heritage as described in [Section 2.2.1](#). In this study, it is assumed that this capacity characterizes an aggregated virtual storage PCM or TCM that represents the total capacity of PCM or TCM storages located throughout the national territory. This assumption ignores the actual inter-zonal connection of the electricity grid. It is however important to understand that this value is not publicly available and details are only supplied by the Italian TSO under a non-disclosure agreement, but the scope of the present

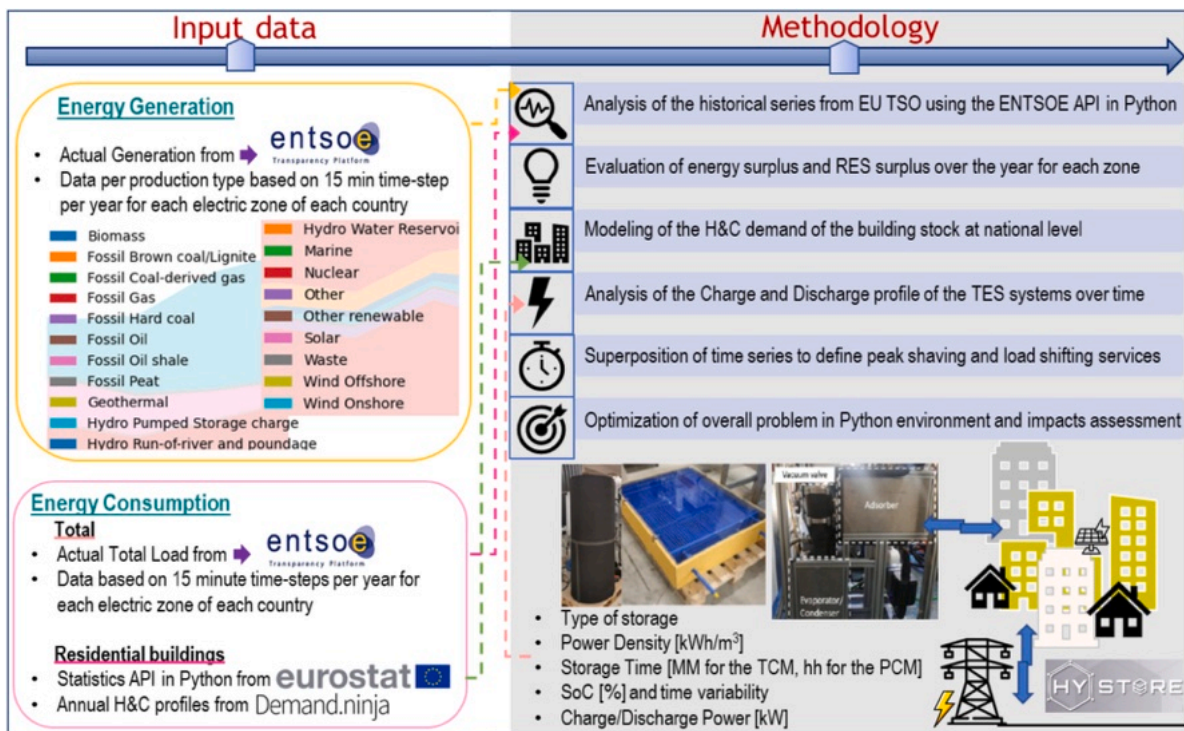


Fig. 1. Flow-chart of the overall methodology for the evaluation of the flexibility and load-shifting potential of TES technologies - PCM and TCM storage systems - at national scale.

paper is to evaluate the feasibility, from an energy perspective, of a scenario with a high-penetration of TES. The geographical-related analyses will be evaluated in future developments of the implementation framework.

- Considering the different storage times of the advanced TES storages, it is assumed that the TCM storage is charged when there is surplus from renewables and the short-term storage is already charged up to its maximum capacity. Utilization of energy from the storage within one month from the beginning of the charging period is allowed. More details about the prioritization rules can be found in Section 2.2.
- Sorption storage can be exploited to satisfy both the space heating and cooling demand of the buildings. However, in order to guarantee the satisfaction of the required temperature levels, the configuration and operation mode of the TCM storage must be oriented in each time-step either to the provision of heating or cooling services. The times to shift from one operation mode, e.g. cooling dominated, to the other, e.g. heating dominated, are of the order of weeks. This implies that the storage capacity residual at the end of the summer cooling season can be employed to satisfy the heating demand using the same TCM storage system. However, due to the non-linearities and complications that the modelling of such constraint would introduce in the optimization problem, for this study it is assumed that a specific thermal energy storage capacity, i.e. an aggregated TCM storage, is used for heating and another for cooling.
- The overall thermal energy storage capacity for heating is equal to the average hourly heating demand over the heating season for the analyzed country (Italy). Similarly, the overall storage capacity for cooling is equal to the hourly cooling demand over the heating season for the analyzed country.
- The PCM/TCM storages considered for the current analysis are not based on a specific storage material or existing configuration. As it will be detailed in Section 2.2, the information needed to model them for the current applications are the storage capacity, the minimum time for charge/discharge and the storage efficiency. The data

selected are based on the average values reported in the literature and therefore can cover several cases.

## 2.1. Materials and data

### 2.1.1. Description of time series data

As described in Fig. 2, the methodology relies on historical series data on energy generation and energy consumption per country provided by EU TSOs and used as input data of the optimization problem. More in specific, monthly energy generation data by type of energy source and actual load data for each hour of a year taken as reference (2022) were downloaded from the ENTSO-E Transparency Platform.

Each country has a different composition in terms of electrical zones. Indeed, the Italian territory is divided into 6 electrical zones - “South”, “North”, “Sicily”, “Sardinia”, “Centre North” and “Centre South”; while other nations, such as Spain and Austria, have a single electrical zone for the entire national territory. Each zone of each country is characterized by a specific electricity generation mix and the RES penetration varies between different states and within the same country.

These historical data series were analyzed in Python environment using the ENTSO-E API.

### 2.1.2. Conversion factors

The Model Predictive Control framework described in Section 2.2, requires the preliminary calculation of the average hourly Coefficient of Performance (COP) and Energy Efficiency Ratio (EER) for heat pumps of each country. As discussed in Section 2.2, the COP and EER values are used to convert the thermal energy requirement for space heating/cooling of each country’s building stock into electricity demand for space heating/cooling and vice versa. On this line, the hourly COP and EER values are used as input parameters of the overall optimization problem.

This sub-section describes the evaluation approach used to calculate the performance coefficients of the heat pump stock of each nation.

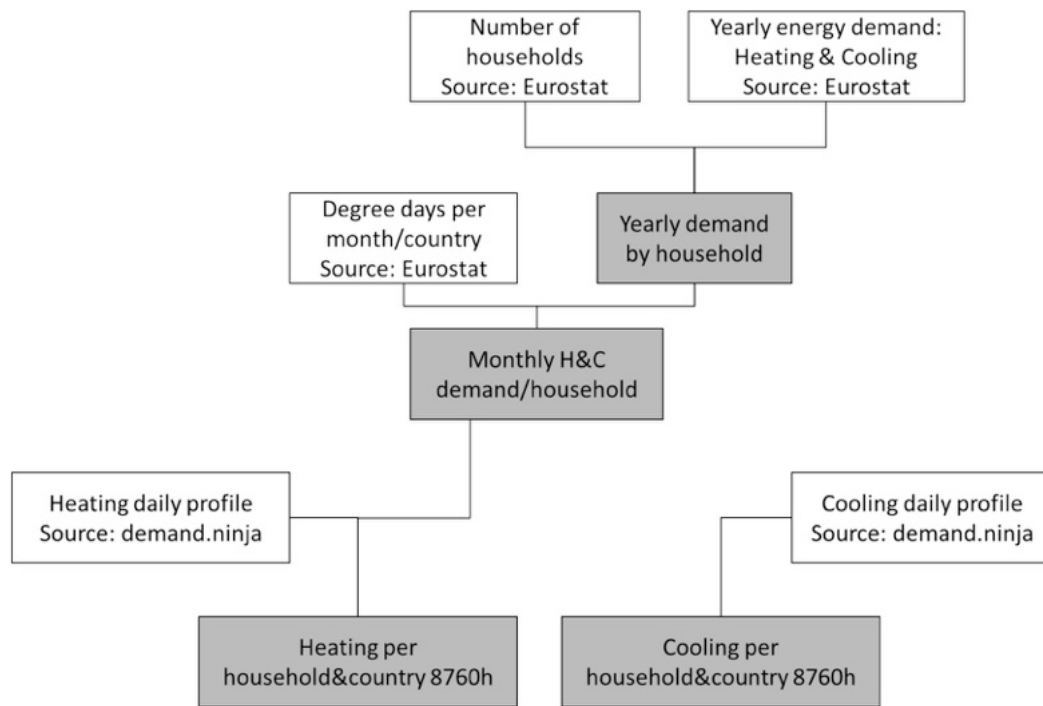


Fig. 2. Conceptual scheme of the methodological approach used for the estimation of the hourly space heating and cooling demand of the building stock for several EU countries.

At each hour, the COP for each heat pump type has been calculated, based on the difference  $\Delta T$  between the operating temperature and the outdoor temperature, i.e. the average temperature of the considered country. Considering the scientific literature [46], the COP values can be calculated as follows for different types of heat pumps used for air-conditioning.

$$COP = 6.08 - 0.0941 \cdot \Delta T + 0.000464 \cdot \Delta T^2 \quad \text{for air - source heat pumps} \quad (1)$$

$$COP = 10.29 - 0.2084 \cdot \Delta T + 0.001322 \cdot \Delta T^2 \quad \text{for water - source heat pumps} \quad (2)$$

$$COP = 9.99 - 0.2049 \cdot \Delta T + 0.001249 \cdot \Delta T^2 \quad \text{for ground - source heat pumps} \quad (3)$$

The average temperature of each nation is calculated in three steps:

- Division of the country in macro-regions with populations comparable to each other, and selection of a representative city for each one of them.
- Retrieval of annual temperature data for each representative city. Such data is available on the Open-Meteo [47] platform, and has been collected with hourly granularity.
- Calculation of the hourly average temperature for the country as the weighted mean of the temperatures of selected cities. The weights used are the population values of each macro-region.

On the other hand, the number of operating heat pumps of each type at national scale has been retrieved from the European Heat Pump Association (EHPA) statistics website [48].

Finally, a weighted average of the three calculated COP resulting from the Eqs. (1)–(3) has been calculated, where the COP for each heat pump type is weighted according to the number of operative heat pumps of that type in the country.

The approach is iterated for the evaluation of the hourly EER time series for different heat pumps, by means of the COP to EER conversion

factor (equal to 3.412) reported in [49].

### 2.1.3. Heating and cooling demand modelling

In order to evaluate the utilization of renewable energy surplus from the electrical grid in the form of thermal energy within household, it is necessary to determine the actual demand for space heating and cooling of the selected countries and their profiles throughout the whole year.

Fig. 2 depicts the conceptual scheme of the methodological approach used for the estimation of the hourly space heating and cooling demand of the building stock for several EU countries.

According to the flow-chart, to achieve a representative model of typical energy consumption, data from multiple sources have been combined. This blend of data allows the creation of consumption patterns at country level for space heating and space cooling production.

The main source of data to size the total amount of electricity used to meet the thermal needs of households is obtained from a publicly available dataset of Eurostat [43], which ensures a reliable source of information. This dataset is compiled with yearly reports of the member states, which include all the sources and uses of energy at households, based on bills, reports from energy producers and other statistical procedures.

To proportionally distribute the yearly amount of electricity for climatization purposes during the months of the year, Heating Degree Days (HDD) and Cooling Degree Days (CDD) data from Eurostat is used [44]. Heating/Cooling Degree days are a quantitative indicator that reflects the energy demand for heating or cooling based on the difference between the average daily temperature and the heating or cooling limit temperature at which it is considered no need of heating or cooling. In Europe, the HDD are the difference between the outdoor average daily temperature and 18 °C, when the outdoor temperature is equal or lower than 15 °C. Similarly, the CDD are the difference between the outdoor average daily temperature and 21 °C, when the outdoor temperature is equal or higher than 24 °C.

Specifically, to obtain the monthly electricity consumption for space heating, the yearly amount of consumed energy is multiplied by the monthly fraction of HDD, and similarly the same has been done for space cooling with the CDD. Once the monthly energy for climatization is

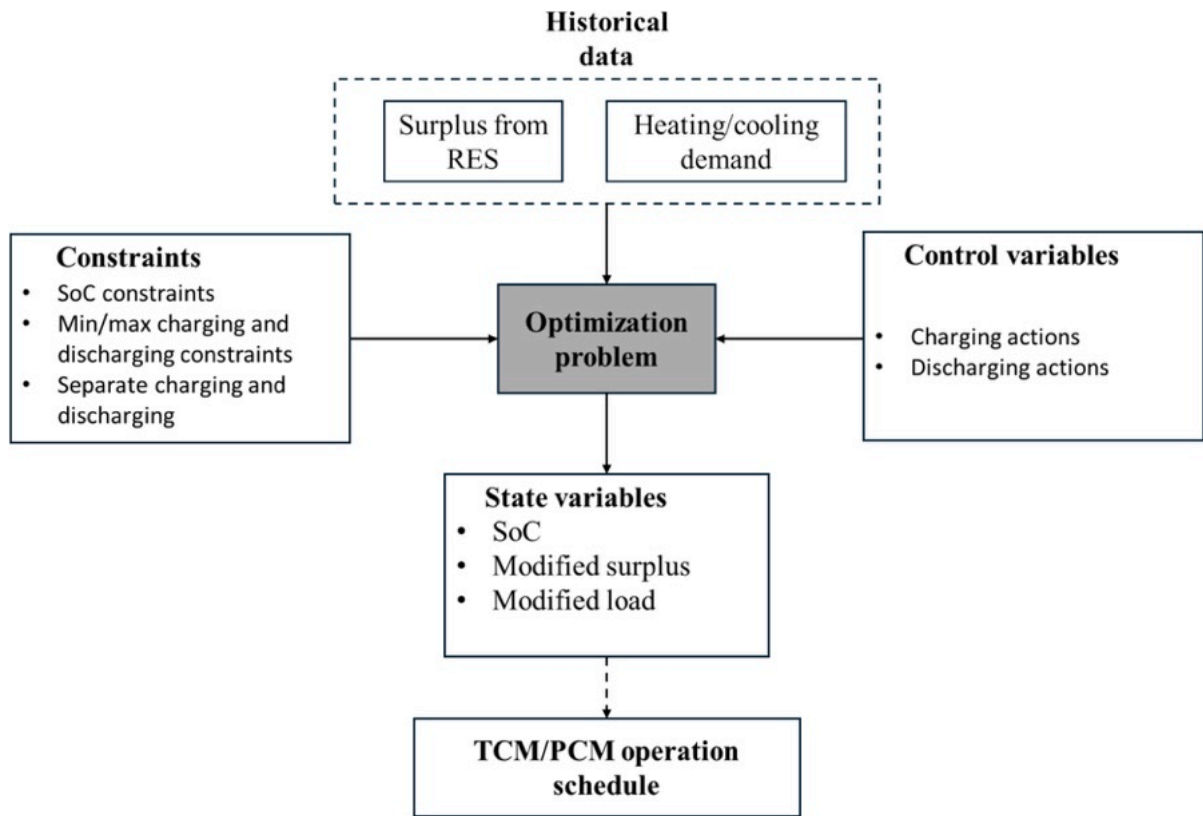


Fig. 3. Optimization scheme of the mathematical programming model for the integration of TES systems into the wider energy system.

known, it is distributed equally across all the days within each month. Finally, to calculate the hourly load demand, the global profiles of heating and cooling [45] are used. These profiles are transformed by calculating the fraction of daily load at each hour, which is then multiplied by the total daily load from each specific month.

## 2.2. Model description

### 2.2.1. Problem description

This section describes the mathematical modelling of technologies, operation and SoC of energy storage; technical and logical constraints and the interaction with the electricity market. Furthermore, this section illustrates the implementation of the overall problem from a predictive perspective and the implementation of the optimization in Python environment.

Fig. 3 presents the optimization scheme of the mathematical programming model for the integration of TES systems into the wider energy system.

As illustrated, the simulation environment is designed to optimize the operation of TES systems within a predictive framework, ensuring efficient use of renewable energy surplus to meet anticipated heating and cooling demands.

On this line, the MPC framework identifies the optimal schedule of charging and discharging processes of TES aggregated storages according to the SoC constraints.

The proposed simulation environment provides a robust framework for analyzing and optimizing the operation of TES systems under various renewable energy and demand scenarios, ensuring energy-efficient and sustainable grid-level surplus operations.

The following notation for the different types of thermal energy storage systems simulated is used:

- PCM\_h is the overall thermal energy storage capacity of PCM storage used for space heating;

- PCM\_c is the overall thermal energy storage capacity of PCM storage used for space cooling;
- TCM\_h is the overall thermal energy storage capacity of TCM used for space heating;
- TCM\_c is the overall thermal energy storage capacity of TCM used for space cooling.

### 2.2.2. Mathematical programming and MPC framework

This section describes the mathematical formulation of the optimization problem and the development of the Model Predictive Control (MPC) framework in Python environment.

Considering the first methodological step, related to the analysis of ENTSO-E historical data series, the total actual electricity generation from the zonal electricity mix,  $G_{el,i}$  is calculated according to Eq. (4).

$$G_{el,i} = \sum_{j=1}^n k_{i,j} = k_{1i} + k_{2i} + \dots + k_{ni} \quad (4)$$

where  $k_{i,j}$  is the electricity generated [MWh] by the j-th production technology of the zonal electrical mix at each time step i, and n is equal to the total number of energy generation technologies constituting the zonal electrical mix in each time step, i.e. 1 = geothermal plants, 2 = oil generation systems etc. In this scenario  $k_j$  is derived from the historical time series of data as well as the total actual energy consumption  $D_{el}$ . Starting from  $D_{el,i}$  and  $G_{el,i}$ , the electricity surplus generated from Renewable Energy Sources (RES) of the base case,  $Su_{el,i}$  can be evaluated as the difference between energy generation and the energy provided by the grid electricity storage of the zonal electricity mix – i.e. hydro water reservoir and hydro pumped -  $S_{el}$ , and the electricity demand of each zone.

$$Su_{el,i} = \sum_{j=1}^n k_{i,j} \Big|_{j=RES} + S_{el,i} - D_{el,i} \quad (5)$$

Considering the conceptualization of the MPC framework, the research idea involves the modelling of the TES upscaling scenarios at the national scale and according to the historical series from EU TSOs, therefore starting from the real data for generation and consumption.

According to this perspective, the aggregated contribution of the PCM/TCM aggregated thermal energy storage can be formulated as follows:

$$S_{i, TES} = \alpha_h \bullet x_{i, TCM\_h} + \alpha_h \bullet x_{i, PCM\_h} + \alpha_c \bullet x_{i, TCM\_c} + \alpha_c \bullet x_{i, PCM\_c} \quad (6)$$

where  $\alpha_h$  and  $\alpha_c$  are the conversion factors from thermal energy to electrical energy, discussed in Section 2.1.2, for heating and cooling respectively, and  $x_i$  represents the thermal energy released from each type of storage during the discharge phase at the time  $i$ .  $y_i$  is defined as the electrical energy stored inside the storage as an input at the time  $i$  during the charge phase. By combining this term with the overall energy consumption, a modified profile of the energy demand is obtained (Eq. (7)).

$$D_{mod,i} = D_{el,i} + y_{i, TCM\_h} + y_{i, PCM\_h} + y_{i, TCM\_c} + y_{i, PCM\_c} + \alpha_h \bullet x_{i, TCM\_h} + \alpha_h \bullet x_{i, PCM\_h} + \alpha_c \bullet x_{i, TCM\_c} + \alpha_c \bullet x_{i, PCM\_c} \quad (7)$$

where  $y_{i, TCM\_h}$ ,  $y_{i, TCM\_c}$ ,  $y_{i, PCM\_h}$ ,  $y_{i, PCM\_c}$  represent the electrical energy that is used for charging and  $x_{i, TCM\_h}$ ,  $x_{i, TCM\_c}$ ,  $x_{i, PCM\_h}$ ,  $x_{i, PCM\_c}$  for discharging the TCM\_h, TCM\_c, PCM\_h and PCM\_c aggregated storage at time  $i$ , respectively.

The SoC update rules are defined according to Eqs. (8)–(11)

$$SoC_{i, PCM\_c} = SoC_{i-1, PCM\_c} + 100 \cdot \left( \frac{y_{i, PCM\_c} \cdot EER_i \cdot \eta_{PCM, ch} - x_{i, PCM\_c} \cdot EER_i \cdot \eta_{PCM, disch} - loss}{Cm_{PCM\_c}} \right) \quad (8)$$

$$SoC_{i, PCM\_h} = SoC_{i-1, PCM\_h} + 100 \cdot \left( \frac{y_{i, PCM\_h} \cdot COP_i \cdot \eta_{PCM, ch} - x_{i, PCM\_h} \cdot COP_i \cdot \eta_{PCM, disch} - loss}{Cm_{PCM\_h}} \right) \quad (9)$$

$$SoC_{i, TCM\_c} = SoC_{i-1, TCM\_c} + 100 \cdot \left( \frac{y_{i, TCM\_c} \cdot COP_{hg, T} \cdot \eta_{TCM, ch} - x_{i, TCM\_c} \cdot EER_i \cdot COP_{ht, c}}{Cm_{TCM\_c}} \right) \quad (10)$$

$$SoC_{i, TCM\_h} = SoC_{i-1, TCM\_h} + 100 \cdot \left( \frac{y_{i, TCM\_h} \cdot COP_{hg, T} \cdot \eta_{TCM, ch} - x_{i, TCM\_h} \cdot COP_i \cdot COP_{ht, h}}{Cm_{TCM\_h}} \right) \quad (11)$$

Eqs. (8) and (9) indicate the SoC update rules for PCM storages, where  $y_i$  and  $x_i$  represent the electrical energy that is used for charging and discharging. In order to correlate the electrical energy with the absolute thermal energy capacity  $Cm_{PCM\_c}$  (MWh), the hourly average COP and EER of air-water heat pumps are used to convert electrical energy to thermal energy. Moreover, a coefficient,  $\eta_{PCM}$ , is introduced to represent the efficiency of PCM storage systems during both charging and discharging phases [50]. Additionally, a constant thermal loss is assumed for PCM storage, implying that in the absence of any charging or discharging activity, the SoC will decrease from its maximum to minimum level within 24 h.

The SoC update rules for TCM storages are presented in Eqs. (10) and (11). Differently from PCM storage systems, a standard conversion factor for high temperature heat pumps,  $COP_{hg, T}$ , is used to convert electrical energy to thermal energy [51]. The efficiencies for discharging are represented by  $COP_{ht, h}$  and  $COP_{ht, c}$  for heating and cooling modes respectively [52].

Furthermore and as per Eq. (12), to minimize energy waste caused by the constant thermal losses in PCM storage, an additional variable called “Forecasted Demand”,  $FD_{i, h\&c}$ , is introduced.  $FD_{i, h\&c}$  ensures that surplus energy is not used to charge PCM storage if there is no anticipated space heating or cooling demand ( $D_{h\&c}$ ) within the next 12 h ( $i + 12$ ), based on the cumulative future demand forecast.

$$FD_{i, h\&c} = \sum_{\tau=i}^{i+12} D_{\tau, h\&c} \quad (12)$$

To model the charge and discharge actions of the storage systems,

several constraints are formulated as follows.

The first constraint applied is related to the operating limits of the storages in terms of SoC. As discussed in the literature [50], it is not

convenient to charge a PCM/TCM storage system until its maximum capacity, because the dynamics of the processes involved becomes very slow once the capacity limit is being approached. A similar approach is

also commonly employed when evaluating the use of batteries in energy management algorithms [53]. Therefore, the operational SoC is constrained between 20 % and 75 % for PCM storage and between 15 % and 80 % for TCM storages for any time point  $i$ .

$$20\% \leq \text{SoC}_{i,\text{PCM\_h\&c}} \leq 75\% \quad (13)$$

$$15\% \leq \text{SoC}_{i,\text{TCM\_h\&c}} \leq 80\% \quad (14)$$

Additionally, a binary variable -  $u_i$  - is assigned to each storage system to ensure that charging and discharging actions are mutually exclusive, preventing both from occurring within the same time step. This reflects the real operation mode of TCM and PCM TES systems, according to which charge and discharge of the same storage cannot occur at the same time. In mathematical terms,  $u_i$  is equal to 1 if the charge is allowed and discharge not allowed, and vice-versa if  $u_i$  is equal to 0.

The operational constraints regarding charging and discharging actions are formulated in Equation from 15 to 22. As an example, Eq. (15) defines the upper bound of the electricity in input to the PCM\_h storage during charge: if the binary variable  $u_{i,\text{PCM\_h}}$  is equal to 1 - e.g. charge is allowed - at each time-step,  $y_{i,\text{PCM\_h}}$  is forced to be lower or equal than the minimum value between the RES surplus and the Forecasted Demand for space heating,  $\text{FD}_{i,h}$ . As a consequence, if the  $\text{FD}_{i,h}$  is equal to zero - e.g. if there is no anticipated demand for space heating in the next 12 h -  $y_{i,\text{PCM\_h}}$  is forced to assume a value of zero, in order to minimize energy waste caused by the thermal losses in the PCM\_h storage.

Vice-versa if the binary variable  $u_{i,\text{PCM\_h}}$  is equal to 0 - e.g. charge is not allowed -  $y_{i,\text{PCM\_h}}$  is forced to be equal to zero. As discussed previously, by means of specific constraints, the optimization problem prioritizes a high frequency of charge and discharge processes of the aggregated PCM storage, and the blocking of charge cycles in case no forecasted demand for space heating is foreseen to take into account the storage mechanism and thermal losses.

On the other hand, sorption storage is not subject to such thermal losses due to its different storage mechanism, which makes it suitable also for long storage applications. This means that no limitations apply to the following hours regarding the TCM charging phase, as the energy can be stored for up to several weeks. It should be noted that, even if sorption storage can be considered a longer-time TES storage, this does not imply that the TCM system cannot be used at shorter times to contribute to the exploitation of the surplus from RES available during peak hours (periods during which both the PCM storage and the TCM are charged if compatible with the SoC limits or if the PCM storage is charged to the maximum level). For this reason, no such constraint for the TCM aggregated storage is included in the optimization framework, which aims to minimize the RES surplus by generating optimal charge and discharge profiles of both PCM and TCM aggregated capacities.

$$y_{i,\text{PCM\_h}} \leq \min_i (\text{FD}_{i,h}, \text{Su}_{el,i}) \bullet u_{i,\text{PCM\_h}} \quad (15)$$

$$y_{i,\text{PCM\_c}} \leq \min_i (\text{FD}_{i,c}, \text{Su}_{el,i} - y_{i,\text{PCM\_h}}) \bullet u_{i,\text{PCM\_c}} \quad (16)$$

$$\alpha_c \bullet x_{i,\text{PCM\_c}} \leq D_{i,c} \bullet (1 - u_{i,\text{PCM\_c}}) \quad (17)$$

$$\alpha_h \bullet x_{i,\text{PCM\_h}} \leq D_{i,h} \bullet (1 - u_{i,\text{PCM\_h}}) \quad (18)$$

$$y_{i,\text{TCM\_h}} \leq \min_i (\text{FD}_{i,h} - \alpha_h \bullet x_{i,\text{TCM\_h}}, \text{Su}_{el,i} - y_{i,\text{PCM\_c}} - y_{i,\text{PCM\_h}}) \bullet u_{i,\text{TCM\_h}} \quad (19)$$

$$y_{i,\text{TCM\_c}} \leq \min_i (\text{FD}_{i,c} - \alpha_c \bullet x_{i,\text{TCM\_c}}, \text{Su}_{el,i} - y_{i,\text{PCM\_c}} - y_{i,\text{PCM\_h}} - y_{i,\text{TCM\_h}}) \bullet u_{i,\text{TCM\_c}} \quad (20)$$

$$\alpha_c \bullet x_{i,\text{TCM\_c}} \leq (D_{i,c} - \alpha_c \bullet x_{i,\text{PCM\_c}}) \bullet (1 - u_{i,\text{TCM\_c}}) \quad (21)$$

$$\alpha_h \bullet x_{i,\text{TCM\_h}} \leq (D_{i,h} - \alpha_h \bullet x_{i,\text{PCM\_h}}) \bullet (1 - u_{i,\text{TCM\_h}}) \quad (22)$$

Eq. (15) and (16) define the constraints governing the charging actions of PCM storages. These constraints ensure that the energy used for charging is limited to the minimum value between the forecasted demand (FD) and available surplus energy ( $\text{Su}_{el}$ ), adhering to the principle of “take as much as you need”. This approach effectively reduces energy lost from PCM storages in scenarios with no demand. On the other hand, Eqs. (17) and (18) establish the discharging constraints, ensuring that storages do not discharge more energy than the thermal demand ( $D$ ). Accordingly, the constraints for TCM storages follow a similar formulation as those for PCM storages, as outlined in Eq. (19) to (22).

Basically, the storage systems are restricted to charge only from renewable energy surplus and discharged solely to meet anticipated space heating and cooling demands.

In this study, the PCM storage systems are prioritized in both charging and discharging phases due to their technology being more suitable for short-storage and in order to exploit the aggregate TCM capacity for longer storage purposes. Therefore, the surplus energy and demand allocated to TCM storages are determined only after the actions of PCM storages have been accounted for.

Moreover, according to Eqs. (23)–(24), an additional weighting factor  $\varphi_i$  is assigned to heating/cooling-related actions, in order to prioritise cooling-related actions when cooling demand is significantly higher, and vice versa for heating-related actions.

$$\varphi_{i,c} = \min_i \left( 1, \frac{D_{i,c}}{D_{i,h} + 0.001} \right) \quad (23)$$

$$\varphi_{i,h} = \min_i \left( 1, \frac{D_{i,h}}{D_{i,c} + 0.001} \right) \quad (24)$$

As for the simulation in Python environment, the optimization problem is formulated as mixed integer linear programming (MILP) and COPT<sup>1</sup> solver is used to solve the problem, since it can efficiently handle mixed integer constraints and large-scale optimization problems.

The simulation time-step is 1 h and the simulation horizon is equal to 12 h.

The optimal planning of the storage systems aims to minimize the renewable surplus from the grid, as described in Eq. (25), which represents the Objective Function (OF) of the problem

$$\text{OF} = \sum_{i=0}^T \left[ \left( \text{Su}_{el,i} - \left( \varphi_{i,\text{heating}} \bullet (y_{i,\text{TCM\_h}} + y_{i,\text{PCM\_h}}) + \varphi_{i,\text{cooling}} \bullet (y_{i,\text{TCM\_c}} + y_{i,\text{PCM\_c}}) \right) \right) + (D_{i,c} + D_{i,h} - (\varphi_{i,h} \bullet \alpha_h \bullet (x_{i,\text{TCM\_h}} + x_{i,\text{PCM\_h}}) + \varphi_{i,c} \bullet \alpha_c \bullet (x_{i,\text{TCM\_c}} + x_{i,\text{PCM\_c}}))) \right] \quad (25)$$

### 3. Results

#### 3.1. Historical series analysis

This section clarifies the results of the preliminary analysis conducted on the historical data series for Italy.

Figs. 4–6 show the main composition of the electricity mix of some of the electrical zones of Italy, representing the monthly aggregate values of energy production by source. The source used for the energy production throughout the year is ENTSO-E Transparency Platform. In such a platform, the data for Italy are divided into six electrical zones: “North”, “Centre-North”, “Centre—South”, “South”, “Sicily”, “Sardinia”. As it will be detailed in the following, the electricity zones where there is

<sup>1</sup> <https://www.copt.de/>.

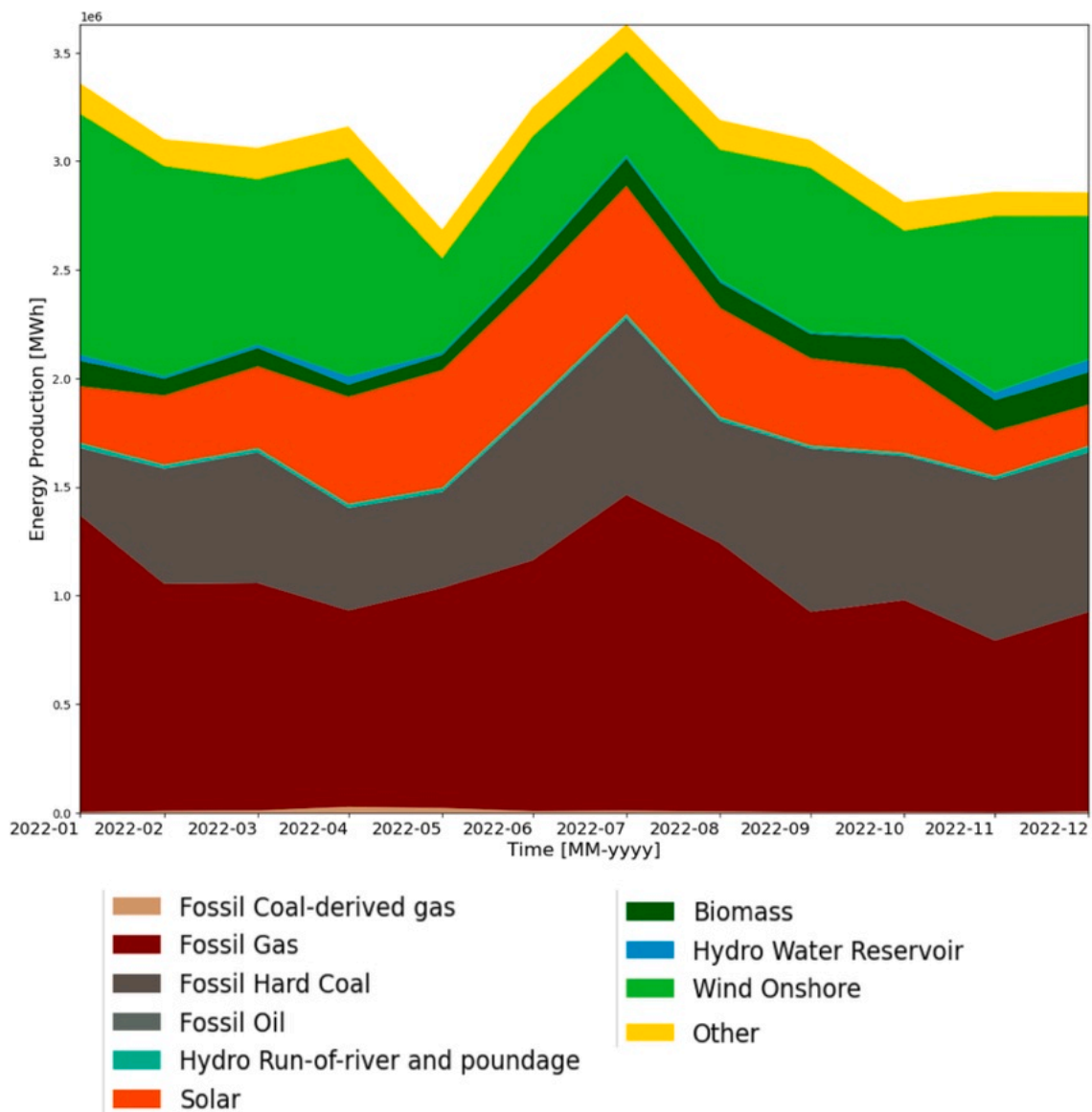


Fig. 4. Main composition of the electricity mix of the “South” electrical zone of Italy: monthly aggregate values of energy production by type of energy source.

surplus are those named “South”, “Centre-South” and “Sicily”, whereas the renewable energy production in “Northern Italy” is limited, therefore it is not described in detail in this section. The data related to the energy generation by type for the other electrical zones are included in the Supplementary Materials.

As per the results of this preliminary analysis, the composition of the electricity mix is variegated among the electricity zones taken into account. Indeed, it varies in terms of the degree of RES penetration and also by type of renewable sources depending on the technological and naturalistic characteristics of the territory. As an example, considering Italy, the predominant renewable source in the South is onshore wind, followed to a lesser extent by biomass and hydro. On the other hand, in the Centre-South of Italy the predominant renewable source is geothermal energy, followed to a lesser extent by wind onshore hydro and biomass. In the “Sicily” region of Italy, however, the incidence of onshore solar and wind is comparable. As per the electrical mix composition of the Centre North of Italy, it is based on the exploitation of solar and geothermal energy to a greater extent and also on wind and hydro to a lesser extent, with a medium degree of RES penetration. Finally, the electrical mix of the “North” electrical zone is characterized by the lowest RES penetration and includes hydro and biomass. Furthermore, it

should be noted that there is a difference, also, in the shape of curves, indicating a seasonal variability of the forecasted load profile depending on the specific area considered. Consequently, this determines a marked territorial variability of the flexibility potential focused on the integration of advanced TES for the optimization of the use of the surplus RES.

As reported by IEA [54], Italian energy system is characterized by a heavy dependence on natural gas, despite the demand for this vector reduced in the last 20 years. Among the renewable energy sources, the one accounting for the highest share is hydropower. This affects the energy systems in two ways: the disparity among zones due to the concentration of hydro reservoirs only in some areas, and the climatic effect, with low hydro availability during the last years due to lower precipitations and overall water scarcity. PV installed capacity is growing, but it still remains minor compared to the other RES and, at the same time, Italy has no CSP plants. These factors explain why, on the one hand, the RES surplus is relatively low and strongly zone-dependent. On the other hand, the RES availability does not follow the typical seasonal patterns of countries that have a higher share of solar-based electricity production.

In order to evaluate the available energy for charging the storages, the temporal distribution from RES is shown in Fig. 7 shows the map of

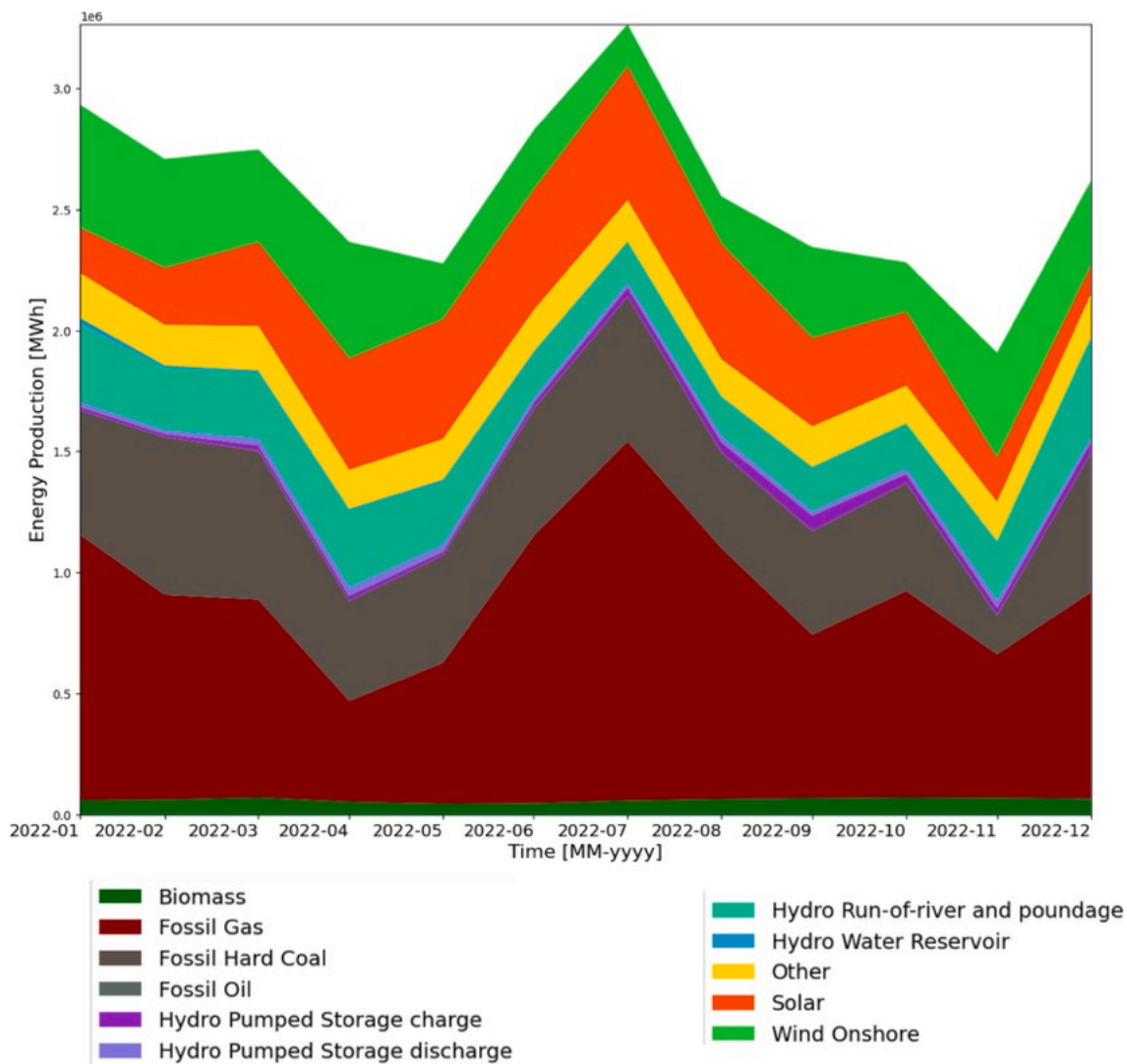


Fig. 5. Main composition of the electricity mix of the “ Centre South” electrical zone of Italy: monthly aggregate values of energy production by type of energy.

the temporal distribution of the surplus along the hours of the week (y-axis) for the several weeks of the year (x-axis). Positive values according to the colour-bar, to the right of the graph, indicate availability of surplus RES and vice versa for negative ones.

As per the results, the area with the highest frequency and intensity of surplus is the “South” corresponding to South Italy. The highest peaks in the surplus are obtained in the zones of Sardinia, Sicily, and South Italy, even though the number of hours with surplus also in Sardinia is limited. It is also interesting to notice that the Centre-North Italy zone presents a very regular pattern of electricity consumption, with increased demand during working hours on Monday to Friday, and a strong reduction during the middle weeks of August and the last week of the year, corresponding to the common holiday period in Italy. This result is of particular interest because of the possibility of exploiting the mid-to-long term storage, that can be effectively charged during these low-demand periods lasting for several hours.

One peculiarity of Italy is the higher concentration of RES surplus occurs during the winter months, with higher potential of the heating season for this kind of flexibility applications.

Globally, considering the case of Italy, the number of hours during which there is surplus of renewable energy is equal to 1899 h with a total amount of 1256.13 GWh across the year and peak values of about 2827 MWh.

These preliminary considerations are useful for scenario planning, as

they provide guidelines regarding the thermal energy storage capacity of PCM/TCM systems used for space heating and cooling. For the present case, as mentioned in Section 2, the results were used to calculate the average heating and cooling demand per hour, which represents the simulated overall storage capacity.

### 3.2. Flexibility assessment and optimization

This section summarizes the main findings of the flexibility assessment based on the evaluation of the performances of the MPC scenario. As discussed, this article presents the outcomes from the optimization framework, based on the concept of sector coupling to provide flexibility services, for Italy. In this optimization scenario, it is worth introducing the concept of low penalty and high penalty periods: low penalty (lp) periods can be defined as hours during which there is surplus from RES, as discussed in the previous section, and vice-versa for high penalty (hp) periods. The final aim of the MPC algorithm is to shift the load from higher penalty periods to low penalty periods in order to minimize the overall surplus RES and optimize the coverage from RES of space heating and cooling demand of the national building stock. In addition, the baseline scenario, i.e. the case of electricity consumption and RES surplus as taken from ENTSO-E data, is defined as Reference (Ref.) case, whereas the “optimised” scenario with the introduction of TES is defined as Flexibility (Flex.) case.

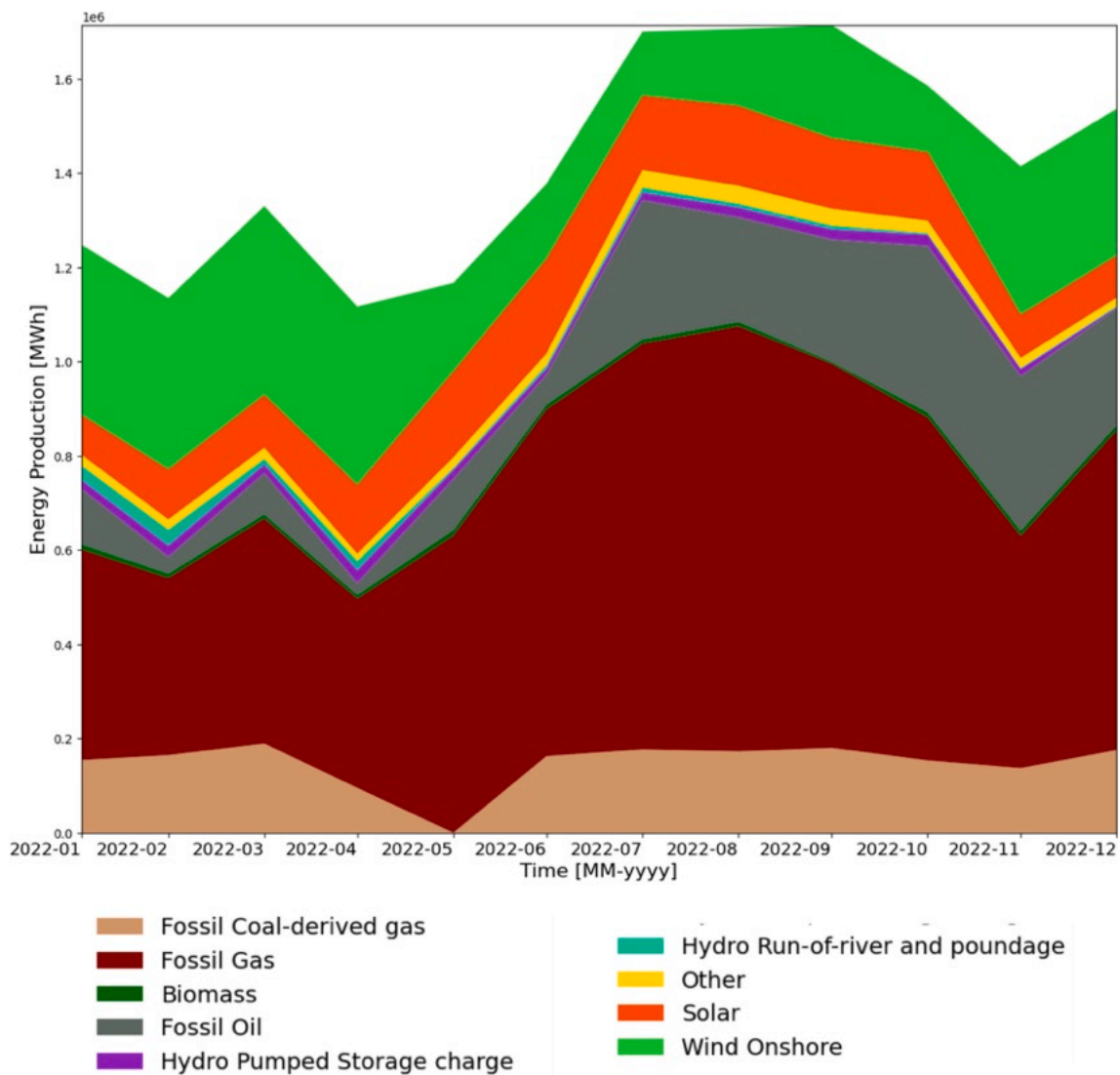


Fig. 6. Main composition of the electricity mix of the “Sicily” electrical zone of Italy: monthly aggregate values of energy production by type of energy.

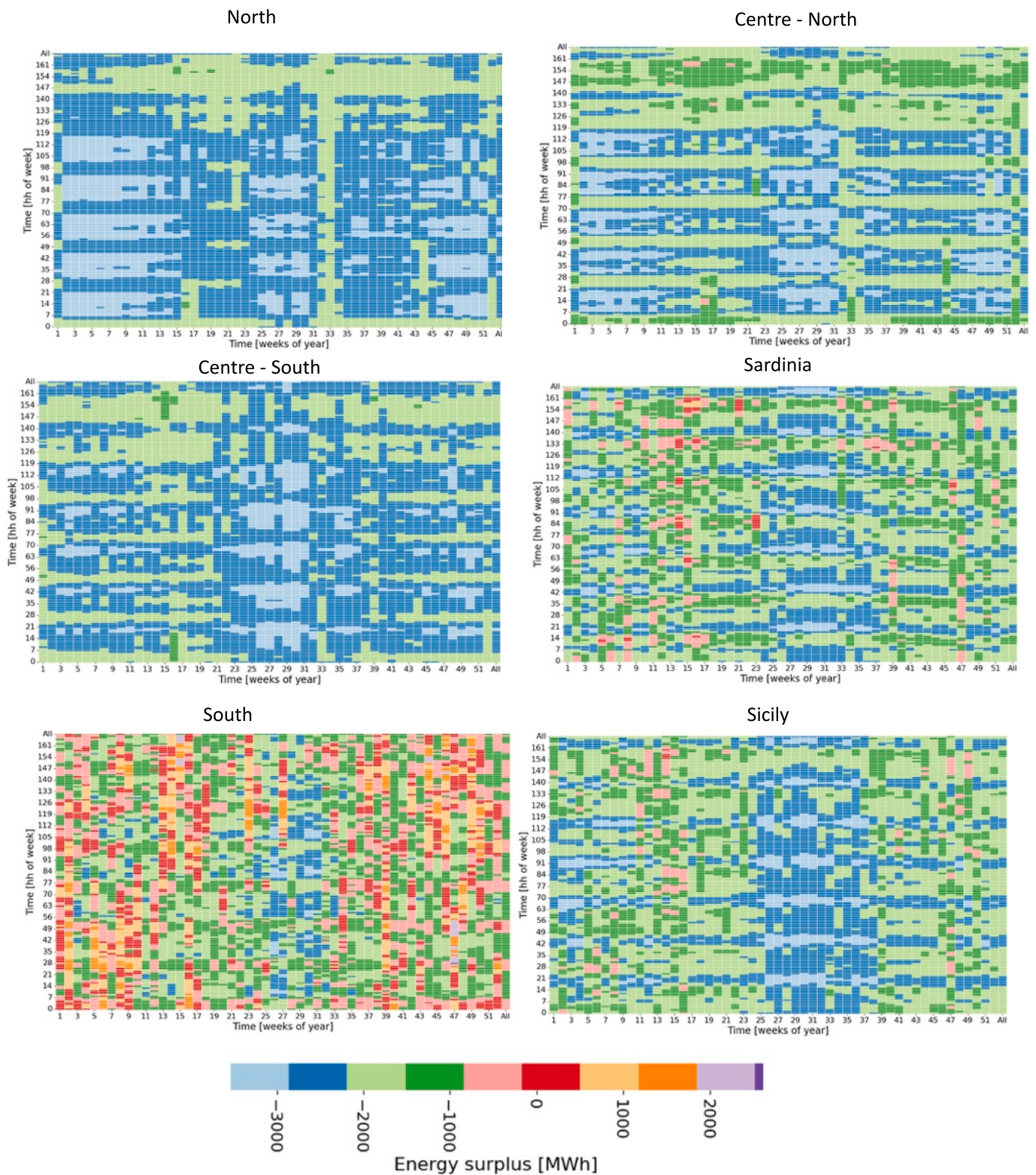
As mentioned in Section 2 the overall thermal energy storage capacity for space heating and cooling of the aggregated thermal energy storage systems is equal to the average hourly thermal energy demand over the heating and cooling season. This results in an overall thermal energy storage capacity for heating of about 1992.22 MWh<sub>th</sub> (thermal) and 26,889.60 MWh<sub>th</sub> (thermal) for cooling to be equally divided between TCM and PCM storage (i.e. about 996 MWh<sub>th</sub> for each storage type used for heating - TCM<sub>h</sub> and PCM<sub>h</sub>).

### 3.2.1. Dynamic behaviour

In order to better understand the optimization carried out by the model, it is worth considering some exemplary days. As previously mentioned, during winter there is a wide availability of RES, that can then be used for charging the storages. Therefore, as an example, three days from 03/01/2022 to 05/01/2022 are shown in detail in Fig. 8. Fig. 8a shows the electricity demand for space heating in the Ref. case (black line) and Flex. case (pink line). The grey bars indicate the low penalty periods. The chart shows a clear shift in the energy used: in the Flex. case, during lp periods there is a higher usage of energy compared to the Ref. case, up to 20 % higher. It corresponds to the available surplus during the days, that is used to charge the storages. In contrast, during the subsequent hp. hours, a significant reduction of the electricity import from the grid can be observed due to the energy discharge from

the TES storage (the periods where the pink curve is below the black one). For the selected days, the storage can supply energy for almost 6 h/d. For all the periods where there is no surplus and the storage has no capacity available, then the two curves for the Flex. and Ref. period are perfectly superimposed.

Fig. 8b and c shows the temporal trend of the SoC of the TCM<sub>h</sub> and PCM<sub>h</sub> TES, respectively. Both storage types are charged until their maximum allowed value of State of Charge (SoC<sub>max</sub>). PCM and TCM charging processes occur at the same time during some hours, since, after one is fully charged, the surplus is used to charge the other type of TES storage. However, it should be noted that, as discussed in the Methodology section, PCM charging and discharging processes are prioritized over TCM ones. This is clearly shown by analyzing the periods in which both storages are charged at the same time: considering the 04/01/2022 from midnight to midday and 05/01/2022 from midnight to midday (the red and violet rectangles in the figure): the SoC of both storage types increases and decreases with frequent cycles. For each of these cycles, the charge and discharge frequency of the PCM storage is higher than the TCM storage, and the value of  $x_{PCM,h}$  is higher than  $x_{TCM,h}$ , since the surplus is used, at first, to charge the PCM storage and only after it reaches the SoC<sub>max</sub>, then it charges the TCM. Furthermore, the model allows simultaneous PCM charging and TCM discharging if the state-of-charge constraints are satisfied, i.e. if in the



**Fig. 7.** Electricity surplus from Renewable Energy Sources (RES) in the electricity mix of the electrical zones of Italy: map of the temporal distribution of the surplus along the hours of the week (y-axis) for the several weeks of the year (x-axis). Positive values according to the colour-bar, to the right of the graph, indicate availability of surplus RES.

presence of surplus RES and if  $SoC_{pcm,i} < SoC_{pcm,max}$  and  $SoC_{tcm,i} = SoC_{tcm,max}$ .

The prioritization rules are also clear in the periods where the surplus is not enough to charge both types of storages (see the green rectangle in

the Figure): in this case the PCM storage is charged/discharged twice, whereas the TCM storage is employed only for charging.

During these three days taken as an example, a load-shifting degree towards low penalty periods of about 10.82 % is achieved compared to

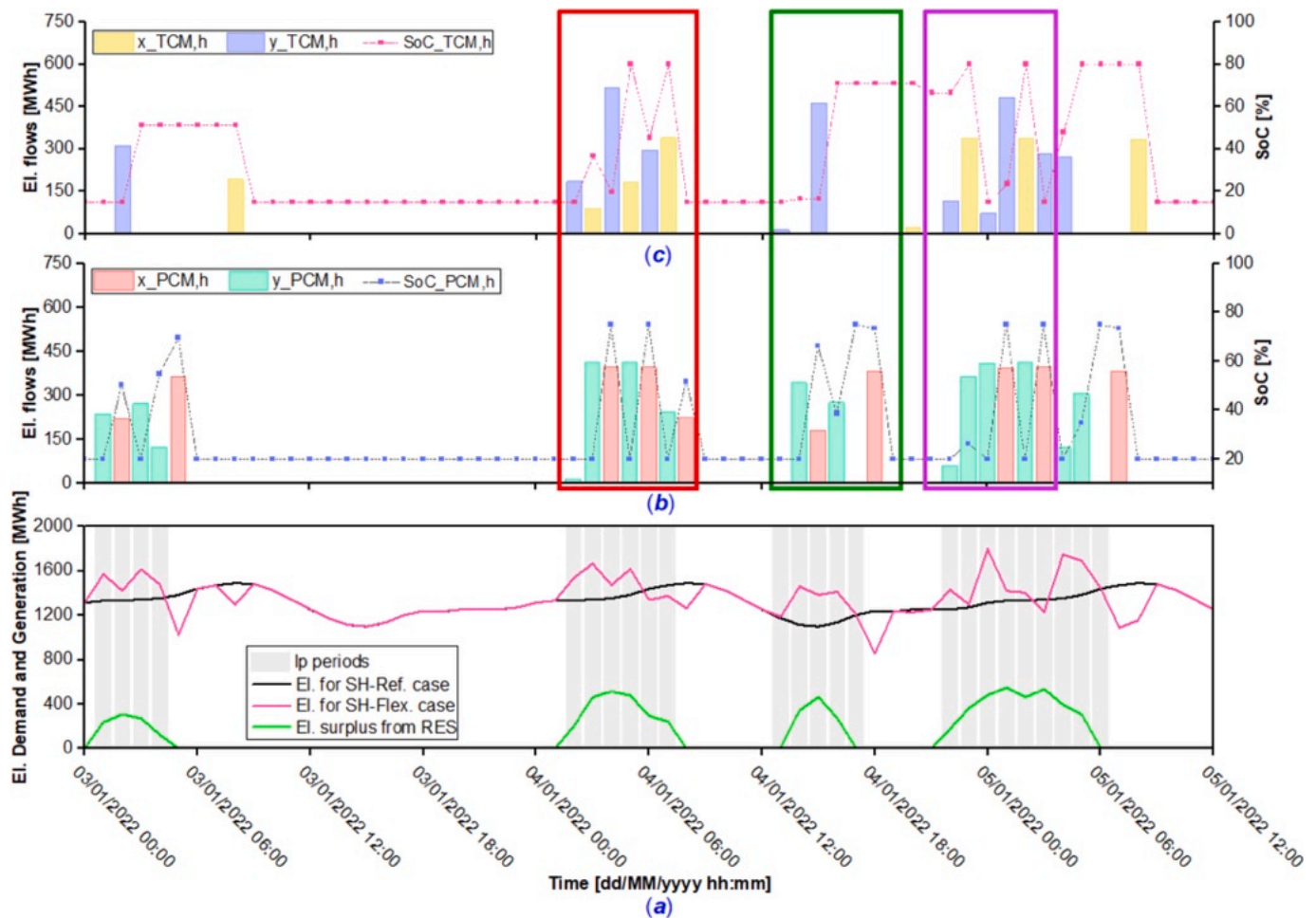


Fig. 8. Dynamics of main variables of the optimization scenario for 3 days of the winter period taken as an example, for Italy. From the bottom to the top: hourly profiles of the electricity demand for space heating (SH) in the Ref. and Flex. case and visualization of the low penalty (lp) periods; hourly profiles of the input (charge) and output (discharge) energy flows and SoC of the aggregated PCM storage and TCM storage.

the reference case. In particular, the energy demand for SH that occurs during low penalty hours is equal to the 408 GWh in the Flex. case and 364 GWh in the Ref. case and the surplus RES is reduced by 88 %. The amount of electricity charged, during low penalty periods (i.e., hours of surplus RES), into the PCM<sub>h</sub> and TCM<sub>h</sub> aggregated storage is, respectively, equal to 4836.28 MWh and 3561.59 MWh and 0 MWh during high penalty periods. On the other hand, the equivalent electric energy corresponding to the discharged heat is equal to 3704.59 MWh and 2181.47 MWh for the PCM<sub>h</sub> and TCM<sub>h</sub> systems, respectively.

On a monthly basis, the number of hourly charging cycles of the aggregated PCM<sub>h</sub> storage during January is equal to 140, while the charging frequency of the aggregated TCM<sub>h</sub> storage is about 97 cycles/MM.

### 3.2.2. Yearly results: state of charge

Figs. 9 and 10 provide the colour-maps of the temporal distribution of the State of Charge (SoC) of the aggregated PCM<sub>h</sub> and TCM<sub>h</sub> storage, respectively, used for space heating along the several days of the year (y-axis) and for the 24 h of the day (x-axis). The colour scale of the two charts is the same, thus allowing a direct comparison of the SoC at each hour. It is evident that the TCM<sub>h</sub> storage has an average SoC that is lower than the PCM<sub>h</sub>, as explained in the previous section. During the summer months (days approximately from 146 to 260) the TCM<sub>h</sub> storage is not used and the PCM<sub>h</sub> storage is used seldomly, due to the presence of a small residual heating demand in very cold zones in Northern Italy. The colour variations along the x-axis represent the

charging and discharging cycles over the day. During the winter period, charging and discharging processes are frequent, as can be seen from the colour variation from red to yellow-green-blue. This trend clearly highlights the peak shaving and load shifting possibilities arising from the use of the two types of storages, due to a non-regular pattern of the RES generation and therefore of RES surplus. The fact that the storages are charged and discharged multiple times over the day also indicates that the variability in RES generation requires multiple activations of the storages over the day. At the same time, the frequent discharging actions during winter clearly indicate that appropriate energy management of the storages for maximisation of self-consumption (i.e. minimization of the surplus of energy from RES) requires the use of a system that is capable of withstanding several cycles during the year. This clearly represents an advantage of TES over batteries, since batteries still have a limited number of cycles before their State of Health (SoH) decreases to unacceptable values. By comparing the two pictures, it is possible to notice that, in the periods when there is the highest demand and most variability of RES (black rectangles in the Figures), the PCM TES is charged/discharged more frequently than TCM TES, as expected. This is reflected by the largest red areas in the charts, corresponding to the fact that the higher SoC is maintained for a longer time. On an annual basis, the number of hourly charging cycles of the aggregated PCM<sub>h</sub> storage is equal to 1099 per year, while the charging frequency of the aggregated TCM<sub>h</sub> storage is about 748 cycles/y. On the other hand, the number of hourly discharging cycles of the aggregated PCM<sub>h</sub> storage is equal to 1057 per year, while the discharging frequency of the aggregated TCM<sub>h</sub>

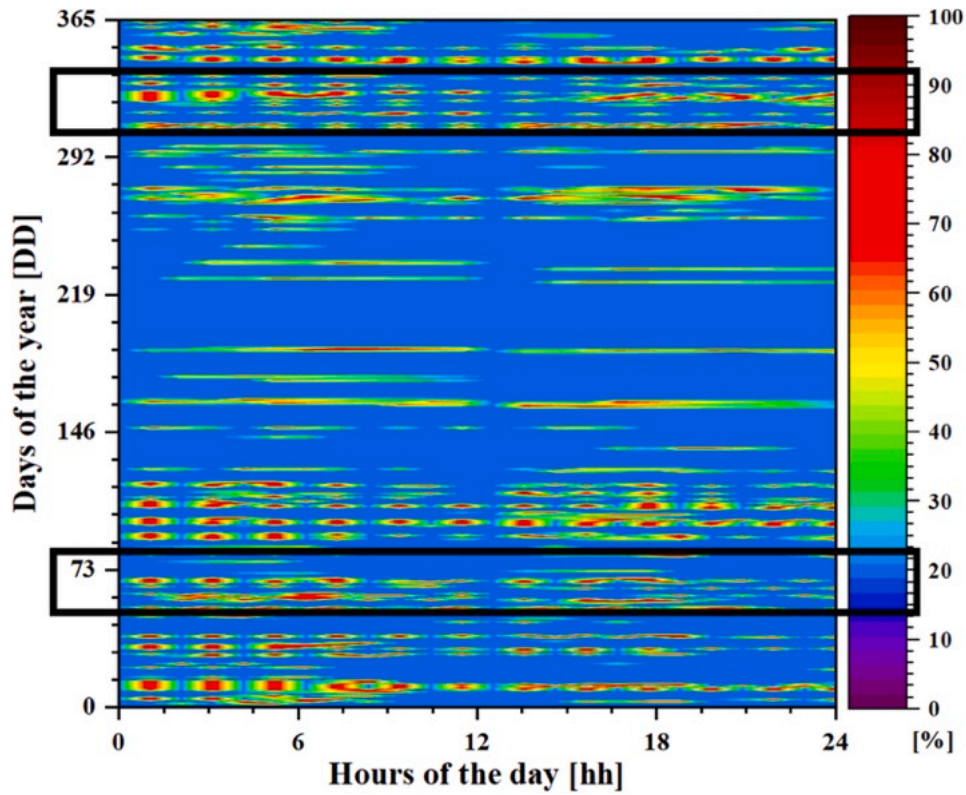


Fig. 9. Colour-map of the temporal distribution of the State of Charge (SoC) of the aggregated PCM storage used for space heating (PCM\_h) along the several days of the year (y-axis) and for the 24 h of the day (x-axis).

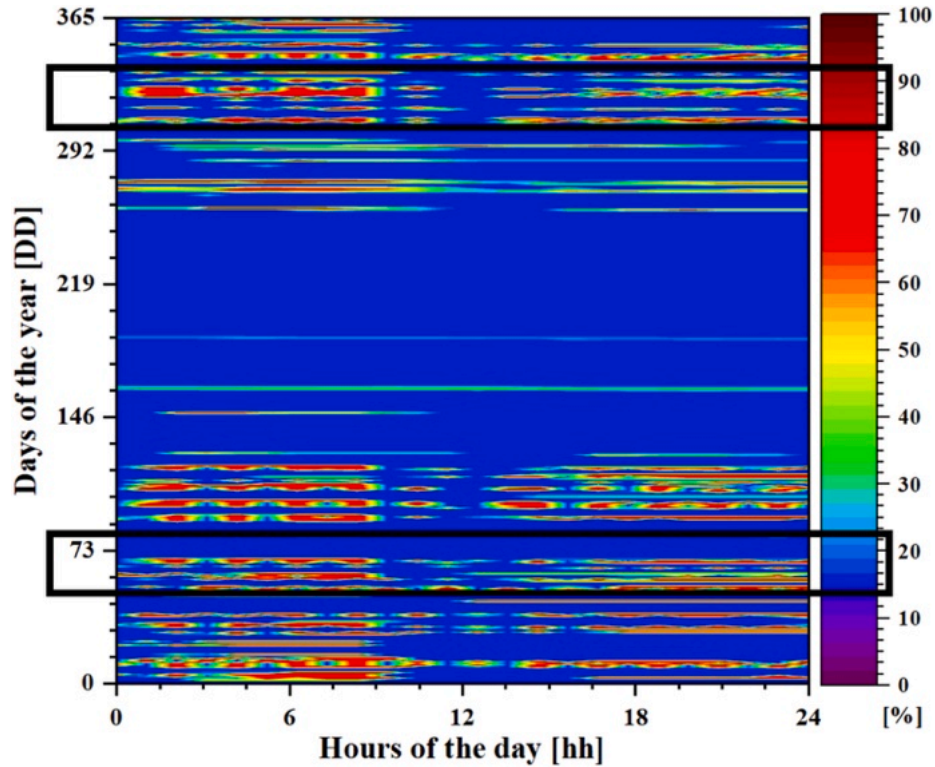


Fig. 10. Colour-map of the temporal distribution of the State of Charge (SoC) of the aggregated TCM storage used for space heating (TCM\_h) along the several days of the year (y-axis) and for the 24 h of the day (x-axis).

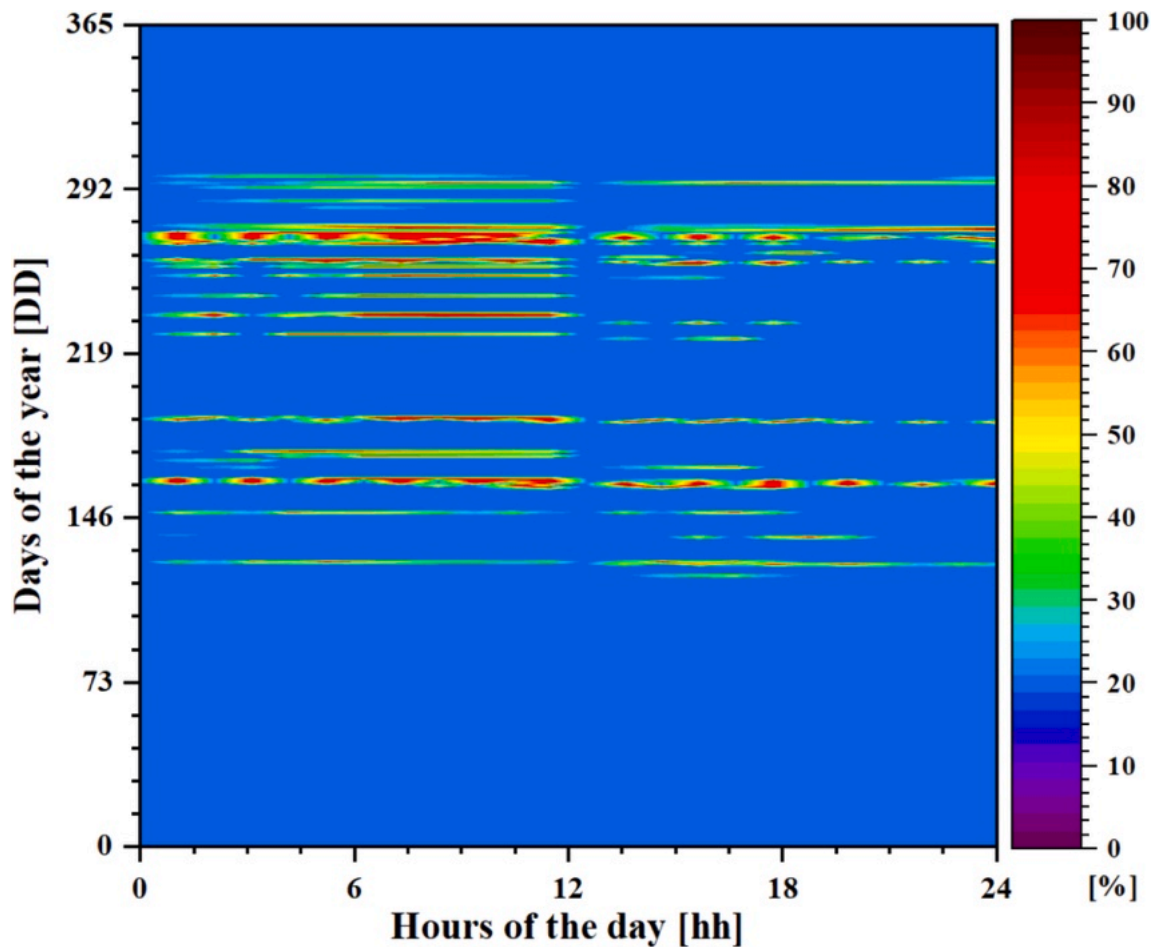


Fig. 11. Colour-map of the temporal distribution of the State of Charge (SoC) of the aggregated PCM storage used for space cooling (PCM\_c) along the several days of the year (y-axis) and for the 24 h of the day (x-axis).

storage is about 648 cycles/y.

Figs. 11 and 12 show the SoC variation over the day (x-axis) and the year (y-axis) for the PCM\_c and TCM\_c storages. The two types of storage are used only during summertime and, partially, during intermediate seasons. Overall, their utilization is lower, in terms of number of cycles over the days and over the months, compared to the storages used for heating. This is mostly due, as highlighted in Section 2.1.1, to the lower surplus available during summer, which reduces the possibility of charging the storages. At the same time, the COP of the heat pumps used for charging the storages is lower during summer compared to winter, thus further reducing the energy available for charging the storages. Detailed data on this pattern can be found in the Supplementary materials, Table 1: Electricity (El.) Demand for space heating (SH) and space cooling (SC) of the national building stock and surplus from RES in the Reference case per month. In particular, the RES surplus in the Ref. case is equal to 149,958 MWh and 238,807 MWh during some months of the winter season (February and November respectively) taken as an example, while it is about 33,336 MWh and 10,047 MWh during July and August. On the other hand, during these summer months, the electricity demand for space cooling is respectively equal to 2,773,082.65 MWh and 2,093,923.56 MW, while the electricity requirement for space heating ranges from 744,977.44 to 486,712.64 MWh during the winter months taken as an example. This difference of orders of magnitude both in the available RES surplus and in the air-conditioning demand to be satisfied determines the lower degree of exploitation of TES devices during the summer season in the case of Italy. As a consequence, the electricity in input during the charge phase of the TCM and PCM storages used for cooling purposes ( $y_{TCM_c}$ ,  $y_{PCM_c}$ )

during the summer season is limited. On a seasonal level, the number of hourly charging cycles of the aggregated PCM\_c storage during summer is equal to 310, while the charging frequency of the aggregated TCM\_c storage is about 225 cycles. On the other hand, the number of hourly discharging cycles of the aggregated PCM\_c storage is equal to 246, while the discharging frequency of the aggregated TCM\_c storage is about 147 cycles. Detailed data on the energy charged/discharged from TES can be found in Supplementary materials (Section 2, Tables 3–4).

As can be seen from the Figures, however, TES systems present a wider use during September when the RES surplus stands at a monthly value of 90,451 MWh with a lower demand for energy for space cooling compared to the other summer months and equal to 605,007.82 MWh.

Extending the research to other countries would allow for a better comparison of the performance during the cooling season of such sector-coupling concepts based on novel TES. Furthermore, it is worth noticing that TCM storages can also be charged with waste heat or heat from district heating, which is under-used during summer or even rejected, and can be used for cooling purposes. In future works, the possibility of having this type of thermal charging instead of power-to-heat methods only will be evaluated, further increasing the flexibility options of the system.

### 3.2.3. TES potential for flexibility

Fig. 13 compares the surplus from RES for the case analyzed considering the reference case (no TES allocation) and the flexibility case according to the rules identified and described in the previous sections. It is possible to notice that there is a reduction of the actual surplus from RES distributed over the year. In quantitative terms, the

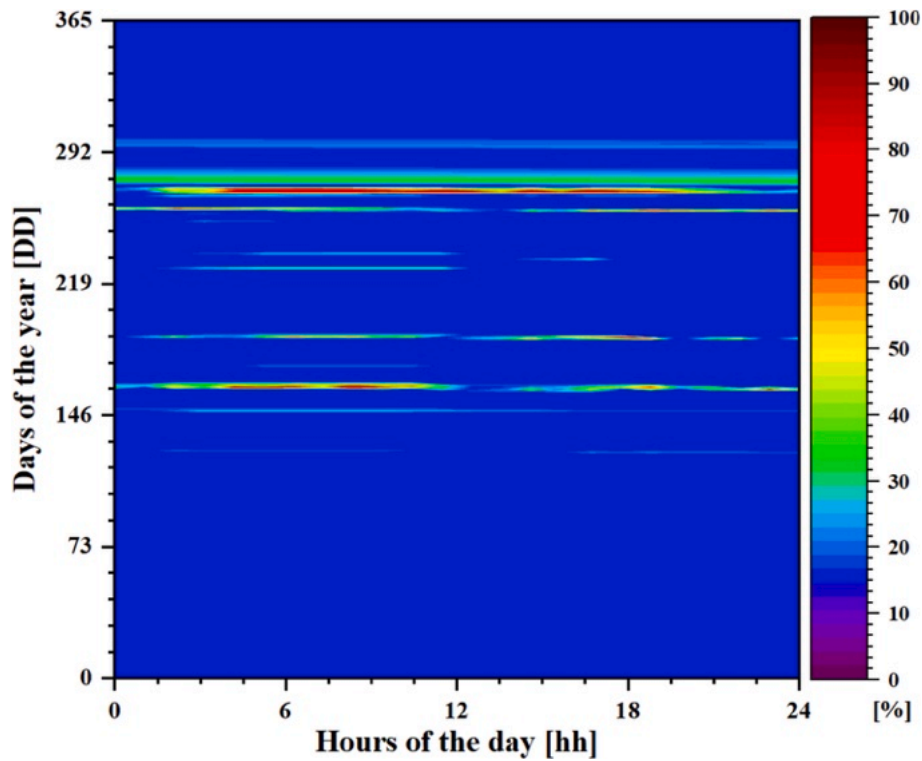


Fig. 12. Colour-map of the temporal distribution of the State of Charge (SoC) of the aggregated TCM storage used for space cooling (TCM\_c) along the several days of the year (y-axis) and for the 24 h of the day (x-axis).

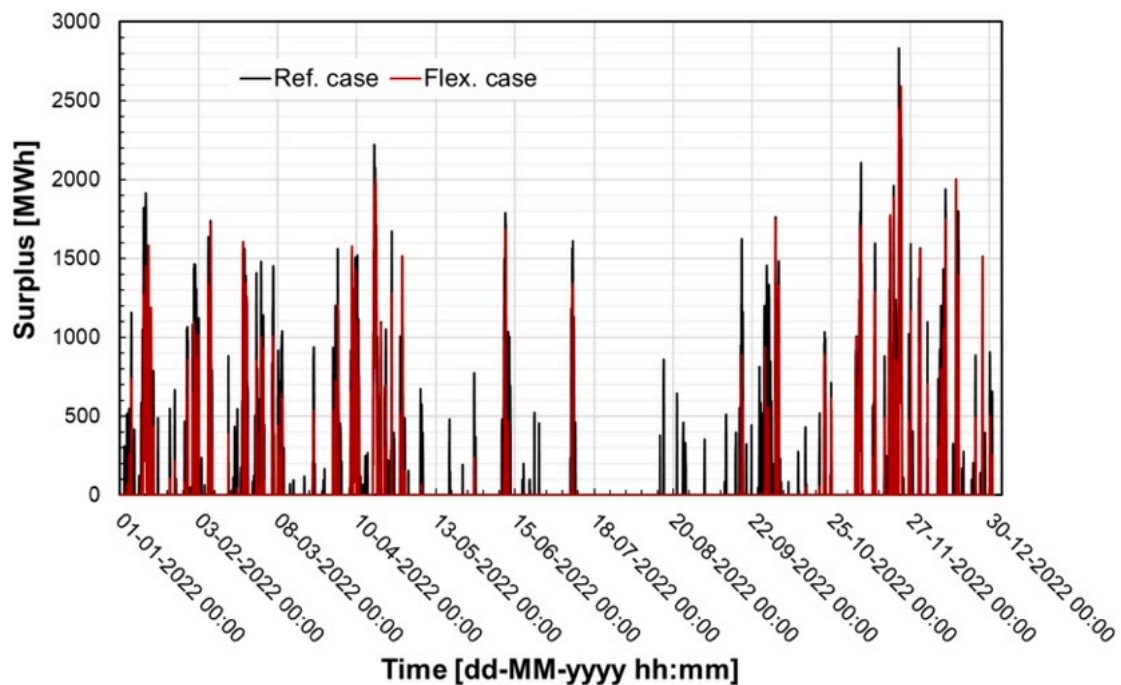


Fig. 13. Comparison of surplus from RES in Italy in the reference and flexibility cases.

proposed TES management scheme achieves a reduction of the annual RES surplus of approximately 58 %. As a result, the number of hours characterized by surplus of renewable energy varies from the base value of 1899 to 925 h. Consequently, the results indicate a load-shifting potential from hp. periods to lp periods of the electricity imported from the grid to meet the space heating demand of the national building stock of about 13 % considering the optimal control of the selected advanced TES

storage systems for meeting the space heating and cooling demand of the national building stock. Considering the current constraints and assumptions, the maximum reduction of the surplus is achieved in intermediate seasons. However, it is possible to notice that, during the heating season, the peaks in the surplus, which correspond also to peaks in RES production, are limited thanks to the use of the thermal storage systems. For instance, looking at the months of January to March, for all

the days in which there is significant RES surplus (>500 MWh), the proposed management system always allows reducing such value by at least 15 %, with peaks of even 40 % (see for instance the month of February). The combination of short-term and mid-term storages also allows reducing the surplus even when the excess in RES production over demand is not in continuous days, but rather sparse over weeks, such as at the end of August. In periods when the storages are under-utilised (due to the low surplus as in summer), they can be always fully charged and used to actually reduce to 0 MWh the excess energy in the network, thus demonstrating the huge potential in the use of the TES technologies as providers of services to the electrical grid.

#### 4. Discussion and future outlooks

The main application of the model that has been investigated in this study concerns the integration of sector coupling concepts leveraging charge and discharge of advanced TES, such as TCM/PCM based storage, in order to minimize the RES surplus available within the national electricity mix. As a consequence, this leads to the minimization of the overall carbon intensity associated with the electricity imported from the grid to satisfy the space heating and cooling demand of the national building stock. In fact, the optimal control of PCM and TCM devices determines a lower use of fossil fuel generation plants, characterized by higher climate-changing emissions and polluting substances production. This effect is particularly significant in countries with an average national electricity mix characterized by a lower RES penetration, such as Italy, compared to other countries, i.e. Sweden etc. In this case, in fact, novel TES storage systems can contribute to load-balancing even during peak hours, at least partially replacing traditional systems with a higher environmental impact such as gas turbines and other fossil-based systems characterized by sufficiently rapid start-up times. More in general, the proposed model and the developed MPC framework can also find application in the field of grid balancing services for the electricity grid and congestion prevention, especially by means of PCM storage by virtue of their rapid start-up time. In addition, TCM storage systems could be exploited in the form of programmable generation/load. Furthermore, this research provides a significant methodological approach that could be exploited in future applications for multi-objective and multi-benefit analyses aimed at minimizing both costs and emissions.

On the other hand, monthly and seasonal TES systems offer the potential to address seasonal disparities in energy supply and demand, while PCM systems are able to cope with sudden daily and hourly load variations.

From the quantitative point of view, the application presented in this document achieves an overall reduction of the surplus RES available within the Italian electricity mix of about 58 % per year and a load-shifting potential of about 13 %. The amount of electricity charged, during low penalty periods (i.e. hours of surplus RES), into the PCM<sub>h</sub> and TCM<sub>h</sub> aggregated storage is, respectively, equal to 295 GWh and 256 GWh during winter. On the other hand, using the conversion factors the electricity provided by the TES storage can be estimated as equal to 250 GWh and 157 GWh for the PCM<sub>h</sub> and TCM<sub>h</sub> systems.

As discussed in the [Result](#) section, the variability in energy production from renewable sources requires multiple activations of storages throughout the day. This finding represents a strength point of TES technologies compared to electricity storage batteries, characterized by a limited number of cycles before their state of health (SoH) drops to unacceptable values [55,56]. This implies a significantly reduced lifespan of electricity storage systems compared to TES storages correctly integrated into the overall electricity network. Regarding the limitations of the research, it is worth noting that since aggregated capacities of TES storage throughout the national territory are considered, the actual inter-zonal connection of the electricity grid is not taken into account. As discussed in the methodology and assumptions section of the paper, data on this are not publicly available and, furthermore, their integration into the model is out of scope of this paper. However, some geographical-

related analyses could be evaluated in future developments of the implementation framework. The storages selected are “virtual” storages, meaning that both the TCM and PCM systems are modelled as a storage capacity, with a certain efficiency and minimum time for charge/discharge, regardless of the storage material. For a more detailed analysis at district level, a consideration on the temperature levels needed to charge/discharge the storages and the needed generators could be added. For an analysis at national level with aggregated storage capacity, this was not deemed necessary.

Furthermore, as in previous studies [31], the balance is evaluated at the country level and the energy flows are not assessed with the detail of the individual electric zone but by considering the aggregate data for the entire nation. On the other hand, compared to the research by Kies et al. [31], the methodological approach presented in this study includes the modelling of the energy demand of residential building stock.

Further future outlooks and some potential developments of the research are presented in the following bullet point list.

- The implementation of the overall framework for other EU countries could result in insightful considerations about the replication potential of such sector-coupling concept in Europe and the definition of a replication plan. Furthermore, the comparative analysis of model performances for several EU countries can guide towards the conceptualization of a tool and tailored-made approaches for the definition of the optimal thermal energy storage capacity for TES – by taking into account the temporal variability of the surplus RES across countries and the intrinsic seasonal variability. Extending the research to other countries would make it more meaningful and allow for a better comparison of the energy systems of the different countries. However, the main aim of the current paper was to present in detail the methodological framework used and provide other researchers with the tools to replicate the results and extend them to a wide variety of other cases.
- As in previous studies, e.g. [31,32], energy metrics were used in this application to assess the performance of the optimization framework in accordance with the objective of the research and the objective function of the optimization problem. A potential development of the research could be focused on the definition of a comprehensive quantification framework for flexibility exploitation based on the evaluation of the operational emissions, peak loads and other flexibility and grid interaction aspects through Key Performance Indicators (KPIs). This perspective could be significant in the case of future applications focused on multi-objective and multi-benefit analyses in order to conduct a trade-off evaluation between multiple scenarios and a step-by-step assessment of co-impacts related to technical feasibility, socio-economic sustainability and environmental compatibility. In this regard, several studies and KPIs on flexibility are defined within the scientific literature. Despite this, research on the flexibility potential of advanced TES remains under-investigated. Therefore, further research efforts are needed in modelling and quantifying flexible systems and buildings integrated with PCM/TCM storage and this research and future developments are framed in this context.
- The flexibility potential of the integration of PCM based thermal energy storage in Domestic Hot Water (DHW) applications at the national scale could be deemed and combined with scenarios focused on the building air-conditioning. Nowadays there is a relevant share of the DHW covered by fossil fuels (i.e. used in gas boiler systems) and the decarbonization of this energy service would contribute to the global decarbonization of the energy system.
- Finally, among further potential applications of the methodology and starting from the validated model, the MPC framework could be downscaled at the scale of smart grid, flexible building cluster or Positive Energy District (PED) and other emerging urban concepts interacting with the overall electricity grid [57,58]. In this case, the application framework could be aimed at reducing the mismatch

between load and RES generation and contribute to the decarbonization and balancing of decentralized prosumer networks.

It is also important to consider that the research here presented is especially interesting when considering the future directions of the energy systems: as highlighted by the Italian Transmission System Operator (TERNA) [59] and by several dedicated studies, it is foreseen that the future energy system will rely on a higher electrification level for the heating and cooling sector [60,61], which would cause, in turn, a higher stress on the electric grid. The electrification would require switching from gas boilers to heat pump-based systems. At the same time, as pointed out by the studies on the resilience of the Italian energy system [60,61], the presence of storage systems that can increase the inertia of the heating/cooling demand with respect of the demand from the electricity grid is paramount. In this respect, the solutions analyzed in the present paper are suitable for the combination with heat pumps for heating and cooling in the residential and tertiary sector and a combination of short term and mid term storage would allow the required inertia. Such storages are also suitable when used in combination with low-enthalpy geothermal energy sources, further remarking their potential in the future energy system with high RES penetration.

## 5. Conclusions

The study presented in this article demonstrated the viability of sector-coupling concepts based on advanced TES, such as Thermo-Chemical Materials and Phase Change Materials energy storage solutions. In particular, the potential increment of the RES energy penetration and load-shifting using advanced TES to meet the heating and cooling demand of the national building stock was assessed. The research focused on developing the modelling framework of the TES upscaling scenarios on the national territory. The models apply real-data of the power grid for energy demand, and validated PCM, TCM data were selected using lab testing or scientific literature. The novelty of the developed approach also aims at minimizing the surplus of renewable energy available within the electricity mix, by means of the integration of TCM and PCM storages with the overall electricity network and optimal control. In this regard, a Model Predictive Control (MPC) framework was implemented and demonstrated using the Italian use-case. The MPC scenario searches for the optimal value of the renewable energy utilization and the grid flexibility, encouraging the decarbonization of the overall energy system and residential sector. To reach the objective, the optimal schedule of charging and discharging actions of short-term PCM and long-term TCM storage solutions was identified, according to the operational and technical constraints.

The results indicate a yearly reduction of the renewable energy surplus by up to 58 %, with particularly high efficiency during the heating season, in which a surplus reduction of 100 % is achieved. These performances are driven by the storage of surplus energy during off-peak periods and its utilization during peak demand periods, addressing both seasonal and daily variability.

Future prospects should be directed towards the analysis of the replication potential of such sector-coupling concepts in Europe. According to a broader vision, tailored-made tools for the definition of the optimal thermal energy storage capacity and indicators could facilitate the replication in other countries.

Furthermore, the MPC framework presented in this study could be scaling-down at district and region level, bridging the research gap on the flexibility potential of advanced TES technologies.

## CRedit authorship contribution statement

**Iliaria Marotta:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yangzhe Chen:** Software, Methodology, Investigation, Data curation,

Conceptualization. **Qian Wang:** Writing – review & editing, Project administration, Funding acquisition. **Joel Nadal:** Software, Resources, Methodology, Data curation. **David Verez:** Validation, Project administration, Funding acquisition. **Fabio Lilliu:** Writing – review & editing, Data curation. **Diego Reforgiato Recupero:** Writing – review & editing, Validation, Methodology. **Marco Calderoni:** Project administration, Funding acquisition, Formal analysis. **Andrea Frazzica:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Valeria Palomba:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

Valeria Palomba reports financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.est.2025.116984>.

## Data availability

Data will be made available on request.

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