**Methodology**

The optimal planning of the storage systems aims to minimize the renewable surplus from the grid, as described in Equation [1].

|  |  |
| --- | --- |
|  | (1) |

Where represent the electrical energy that is used for charging TCM\_h, TCM\_c, PCM\_h and PCM\_c at time , respectively. The simulation time step is 1 hour which is identical to the historical data retrieved from ENTSOE platform, and the simulation horizon is 12 hours.

To model the charge and discharge actions of the storage systems, several constraints are formulated as follows.

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |

After obtaining from literatures [need references], the operational SoC is constrained between 20% and 75% for PCM storages, while 15% to 80% for TCM storages for any time point . The SoC update rules are defined according to Equation [4-7].

|  |  |
| --- | --- |
|  | (4) |
|  | (5) |
|  | (6) |
|  | (7) |

Equations [4, 5] indicate the SoC update rules for PCM storages, where and represent the electrical energy that is used for charging and discharging. In order to correlate the electrical energy with the absolute thermal energy capacity (MWh), the hourly COP and EER are calculated to convert electrical energy to thermal energy. The detailed calculation can be referred to [Add calculation detail]. Moreover, a coefficient, , is introduced to represent the efficiency of PCM storage systems during both charging and discharging phases. 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 hours. The SoC update rules for TCM storages are presented in Equations [6, 7]. Different from PCM storage systems, a standard conversion factor, , is used to convert electrical energy to thermal energy, instead of COP or EER. The efficiencies for charging and discharging are represented by and , respectively.

Furthermore, to minimize energy waste caused by the constant thermal losses in PCM storage, an additional constraint is introduced, shown in Equation [8]. This constraint ensures that surplus energy is not used to charge PCM storage if there is no anticipated space heating or cooling demand () within the next 12 hours (), based on the cumulative future demand forecast.

|  |  |
| --- | --- |
|  | (8) |

The constraints regarding charging and discharging actions are formulated in Equation [9 to 12].

|  |  |
| --- | --- |
|  | (9) |
|  | (10) |
|  | (11) |
|  | (12) |
|  | (9) |
|  | (10) |
|  | (11) |
|  | (12) |

Moreover, an additional weighting factor 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.

|  |  |
| --- | --- |
|  | (13) |
|  | (14) |

Basically, the storage systems are restricted to charging only from renewable energy surplus and discharging solely to meet anticipated space heating and cooling demands. Additionally, a binary variable 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. In this study, the PCM storage systems are prioritised in both charging and discharging phases.

**Software used**

The simulation is formulated in Python leveraging historical data. The optimization problem is formulated as mixed integer linear programming (MILP) and COPT [ref] solver is used to solve the problem, since it can efficiently handle mixed integer constraints and large-scale optimization problems.

**Main implementation highlights**

The simulation environment is designed to optimize the operation of thermal storage systems within a predictive framework, ensuring efficient use of renewable energy surplus to meet anticipated heating and cooling demands. The proposed simulation environment provides a robust framework for analysing and optimizing the operation of thermal storage systems under various renewable energy and demand scenarios, ensuring energy-efficient and sustainable grid-level surplus operations. As validations and applications, the historical national surplus from four European countries (Italy, Sweden, Spain, and Austria) are involved in the simulation under different capacity and demand scenarios. The results imply that the proposed method is able to efficiently store and consume the grid-level surplus leveraging TCM and PCM storage systems, which lays a solid foundation for future demand-side advanced storage systems studies.