Summary

The environmental and energy crisis that our societies are facing demands rapid changes in the global energy sector, necessitating the timely adoption of renewable and sustainable energy sources. However, these sources are either variable or inflexible (in the case of nuclear energy), requiring technologies to provide the flexibility needed by the demand side. In this context, energy storage is a key technology for achieving this flexibility and accelerating the integration of sustainable energy alternatives. Thermal energy storage is one promising option, especially for applications where heat is produced or required. Among the various technologies, latent heat storage using phase change materials has gained scientific and market attention. However, their broader use in industrial, domestic, and building applications is limited mainly by the low thermal conductivity of these materials, which impedes heat transfer, thus adversely affecting storage performance. This research focuses on evaluating the impact of different heat transfer enhancement techniques in phase change materials-based thermal energy storage applications.

First, the focus is on a traditional technique that has been studied for decades: the addition of highly conductive micro or nanofillers to phase change material matrixes. Despite its promising potential, this solution has not achieved the expected performance levels in scientific literature, and research in this area is still ongoing. In this framework, the first part of this thesis examines the addition of highly conductive nanofillers to a paraffin-based phase change material. This study encompasses both material and prototype scales, involving experimental measurements and numerical simulations. The main objectives are to assess the impact of interface phenomena between different materials in these nanocomposites and to develop a numerical method for predicting the nanocomposites effective thermal conductivity. Then, these findings are applied in a case study of a thermal energy storage tank prototype aimed at cooling applications in domestic environments. This study highlights issues identified by the scientific community, such as the challenge of achieving a stable mixture that does not suffer from segregation and the performances of nanofiller additions in terms of effective thermal conductivity which are still far from theoretical expectations.

After confirming the difficulties associated with managing nanofiller techniques, the study explores alternatives, identifying metal wool as a promising, effective, and relatively inexpensive solution, particularly suitable for applications in already existing thermal energy storage tanks. In this framework, a collaborative project between the SMaLL group of Politecnico di Torino and the GREiA research group of the Universitat de Lleida is carried out to investigate the performance of adding metal wool to phase change materials from both experimental and numerical perspectives. The experimental facilities available at Prof. Cabeza's group are utilized to conduct the charging and discharging processes of a thermal energy storage tank containing phase change materials and metal wool. Various configurations of metal wool are tested in an extensive experimental campaign, resulting in significant reductions in discharge times, with decreases of up to 79% compared to the bulk phase change material case. From a numerical perspective, CFD simulations provide valuable insights into the composite behavior and suggest possible optimizations in wool material and configurations. The results of this collaborative project confirm the promising potential of using metal wool to enhance heat transfer in phase change materials.

In summary, this study is driven by the need to enhance heat transfer in phase change materials to achieve thermal energy storage performance levels required from the various (industrial, domestic, buildings, etc.) applications. The thesis primarily focuses on evaluating the impact of two heat transfer techniques on the thermal performance of commercial phase change materials: the addition of nanocomposites and metal wool. While the first approach highlights the challenges associated with nanocomposites, the addition of metal wool yields promising results. Nonetheless, some issues emerg from such analysis, such as the difficulty in obtaining reliable predictions in material properties that does not rely on fitting parameters, as well as the challenge of coupling the geometrical and thermophysical properties of the constituent materials with the overall behavior of the composite. In conclusion, these findings pave the way for further experimental and numerical studies on optimized wool configurations and at larger scales to assess the techno-economic impact of this technology in existing pilot plants and industrial solutions.