Buildings (< 50 kWh/day). Integrated Batteries with Phase Change Materials (PCM) for Peak Shaving and Load Management: The HYBUILD Example

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Abstract The continuous increasing of renewable-based energy systems, both for heating and power generation, at building level requires the development of innovative compact hybrid energy storages. These technologies are able to support the flexible operation of such complex systems, increasing the exploitability of renewables and the overall system efficiency. In this chapter, a brief overview of different storage technologies, such as thermal, electric and hybrid, at building level is provided, mostly focusing on their integration with onsite renewable generation and smart grids. The analysis highlights the relevant role of flexible energy storages at building level as well as the lack of innovative components able to provide multiple services (e.g. heating, cooling, domestic hot water and power) to buildings. In such a background, the experience carried out in the framework of the EU-funded HYBUILD project is described. The overall concept, integrating electric batteries, latent, and thermochemical storages, with highly efficient reversible heat pumps is described, showing the different options developed for continental and mediterranean climates. The fully integrated Mediterranean system, validated both at lab-scale and in a demo building, demonstrated the ability of increasing the share of renewables in buildings, maximizing the self-consumption and increasing the overall energy efficiency of the system.

Keywords Energy storage · Buildings · Batteries · Thermal energy storage · Peak shaving · Load management

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1 Introduction

The increase of the share or renewable energy into the existing power and heating and cooling infrastructure requires overcoming new challenges (Cabeza and Palomba 2020). Energy storage systems contribute to the stabilization of the variable output of renewable energy (Liu et al. 2024). By storing surplus electricity during high-generation periods and discharging it during low-generation periods, energy storage technologies maintain a balance between supply and demand. Another advantage is the enhancement of the scheduling flexibility of renewable energy sources. Therefore, energy storage brings technical, economic and social opportunities in this new energy system. Energy storage technologies include pumped hydro energy storage, compressed air energy storage, flywheels, supercapacitors, thermal energy storage (TES), batteries, and hydrogen storage.

Batteries serve as a prevalent energy storage medium and are typically classified as short-duration storage systems (Liu et al. 2024). TES is often integrated into concentrated solar power (CSP) systems for short-duration storage due with its large capacity and cost-effectiveness, but recently, its potential for seasonal-storage has been demonstrated (Prieto et al. 2024). At building level, batteries are mainly used for short-term electrical storage, while TES technologies can be either used for short-term (sensible and latent TES) or for long-term storage (thermochemical TES). Therefore, hybrid systems using both batteries and TES can give advantages such as flexibility, short- and long-term storage, energy efficiency, etc.

In the present chapter, a brief overview of the current investigations focused on storage integration in buildings is presented. Then, a case study related to the development and demonstration of innovative hybrid energy storage solutions in buildings, carried out in the framework of the Horizon 2020 project HYBUILD (G. A. 768,824) is described.

2 Integrated Solutions for Hybrid Storage and Power-To-X Systems in Building

In the following sections, a brief state-of-the-art related to different energy storage technologies, i.e., thermal, electric and hybrid, employed in buildings to support heating, cooling and power demand is reported. The main advantages and challenges linked to the use of these technologies are discussed to highlight the relevance of the development of flexible and highly efficient storage solutions to support the future energy systems.

2.1 Thermal Energy Storage + Power-To-X

An overview of the potential inclusion of thermal energy storage (TES) and electrical-thermal energy storage (ETES) in the overall energy system is shown in Fig. 1. Excess electricity from renewable energy sources or for grid balancing can be stored in ETES systems for its later use for heating and cooling purposes (Cisek and Taler 2019). It should be highlighted that both TES and ETES can be installed in the generation side of the energy system (for example, coupled to the energy generation system with molten salts storage), in the transmission and distribution section of the energy system (for example, including heating and cooling networks), and in the demand side to directly cover the load of the user.

There are many reasons to add a TES or ETES device in the energy system. One of the key drivers is given by the need to increase the integration of new renewable energy sources (RES) in the grid (especially the intermittent ones such as wind power and solar energy, to reach the target of up to 100% penetration. Research on this topic has been carried out during the last decade at a global level (Jacobson et al. 2015; Child et al. 2018, 2019) and the importance of a proper mix of energy generation technologies and storage solutions was highlighted (Solomon et al. 2017, 2019), especially in view of a trans-national connection of the energy system (Rasmussen et al. 2012). Other reasons are the reduction of the levelized cost of energy (LCoE) via economic optimization with the adequate balance between production and utilization of energy considering power and time (Kiptoo et al. 2020; Timmons et al. 2020) and peak shifting, to avoid curtailment of the energy produced by RES (Beaudin et al. 2010; Bao et al. 2016; Talluri et al. 2019). On the demand side TES and ETES are integrated two-fold. First, storage solutions help matching the generation

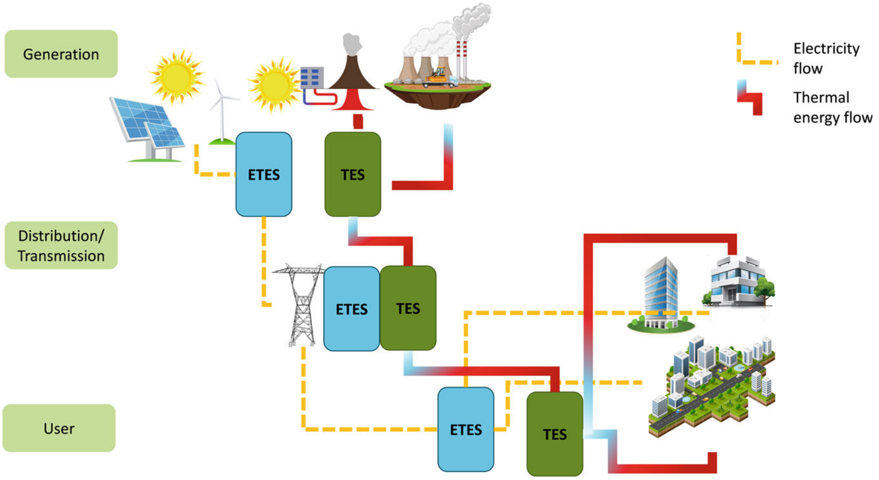

Fig. 1 Possible storage interaction in the energy system. TES, thermal energy storage; ETES, electrical thermal energy storage

capacity with load demand under extremely variable operating conditions to give response to the significant push towards an increased self-consumption and energy balance at district/micro-grid level present today (McKenna et al. 2019). Second, at single building level, TES and ETES are utilized to increase the flexibility of the energy system and achieve contemporarily both human comfort conditions and high efficiency of the system (Palomba and Frazzica 2019; Cisek and Taler 2019).

The need for a combination of solutions for coupling the electricity sector with the heat one has been highlighted in different roadmaps for energy storage technologies (Durand et al. 2013; International Energy Agency 2014; ICEF–Innovation for Cool Earch Forum 2017), but most applications are still linked to the use of electricity storage at the different scales mentioned above.

2.2 Electric Energy Storage + Power-To-X

Power-to-X system architectures need the integration of several technologies able to provide the necessary transport and storage of the energy carriers used. This integration requires a combined and optimized use of the energy resources through the management of their production and utilization which normally does not match in time. To do this, energy storage systems are crucial elements to act as buffers between production and consumption, as represented in Fig. 2. This is particularly true if the electricity carrier is considered, given that the presence of renewables introduces an important factor of uncertainty.

Several technologies were and are developed in recent years to realize storage systems more and more efficient, reliable, affordable and generally more performing. In particular, electrochemical storage systems (batteries) have significantly increased their presence on the market, driven by various sectors such as portable devices, transport and stationary services to the electricity grid. The performances currently offered in terms energy and power density, round-trip efficiency and lifetime have pushed these technologies into common use also in building sector, normally coupled with small renewable energy production systems (solar, wind) (IEA 2024). It is important to underline that, in power to X architectures, batteries are not suitable for seasonal storage because they become uneconomical when the stored energy have to be released in weeks or months (Sterner and Specht 2021). On the contrary, they are superior systems when short-term storage is considered, allowing high flexibility and efficiency in power-to-power systems, as schematically reported in Fig. 3. The presence of the storage can have several impact: it maximize the load and generation match; it can reduce stress on the grid, making it more reliable and potentially delaying the need for costly infrastructure upgrades; it can generate revenue or money saving through optimized management of the energy carriers cost and prices; it is able to face unexpected events, maintaining systems stability and allowing superior user comfort (Airò Farulla et al. 2021).

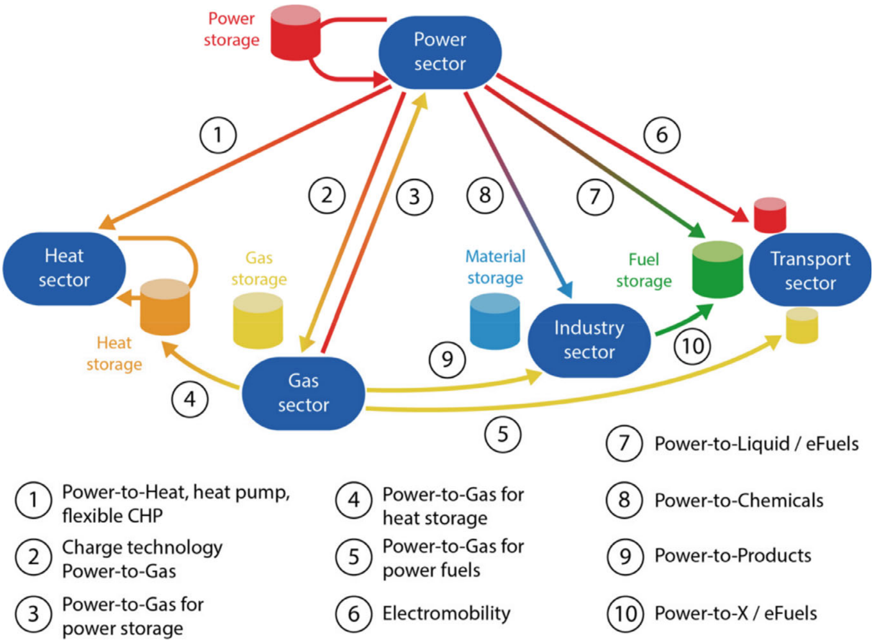

Fig. 2 Sector coupling resulted from power-to-gas and power-to-X (Sterner and Specht 2021)

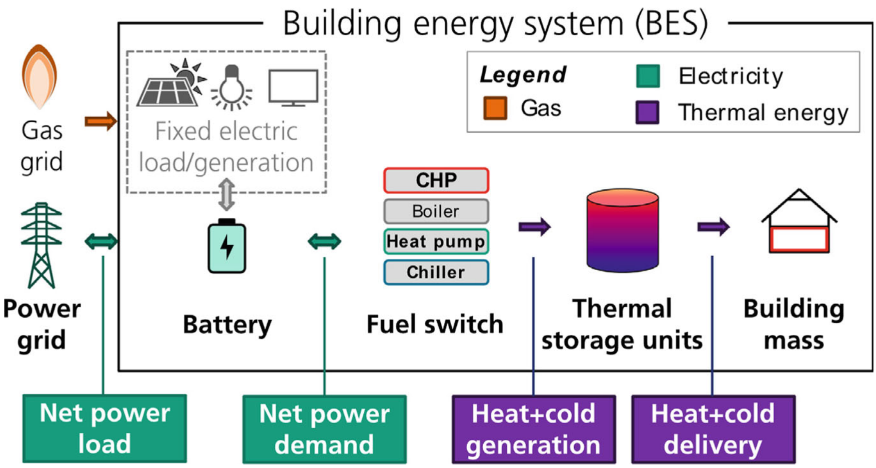

Fig. 3 Building energy system with different flexibility and storage options possible (Klein et al. 2017)

As described in (Rey et al. 2023) the main technology among batteries is currently the Lithium-ion cell (Li-ion). They are nowadays widely used in several application sectors due to high energy and power density, very high round-trip efficiency, good lifetime and rapid charge and discharge times. Different types of lithium battery exist according to active materials used for their realization. Among them, the most important are:

NCA ($Li(Ni,Co,Al)O_2$): the presence of aluminum reduces cobalt use (critical) and also volumetric changes. They ensure long life and overall good performances but lower safety due to cathode instability.

NMC ($Li(Ni,Co,Mn)O_2$): the current most used technology with several different percentages of constitutive components. They offer customizable properties, high capacity, good C-rate and performance. Better safety than NCA but it is still a concerning issue. Stationary market is exploring their use after the first life (second life application).

LFP ($LiFePO_4$): well known for their superior stability, wider temperature window and high lifetime. However, they have a lower nominal voltage and consequent lower energy density. For their characteristics they constitute the dominant technology in Behind the Meter (BTM) applications.

LTO ($Li_4Ti_5O_{12}$): take the name of the different anode material (LTO vs graphite), they offer an exceptional lifetime compared to other lithium batteries and good safety. On the contrary, their cost is the main drawback.

The current evolution stage is called GEN3 with goal of optimized NMC811 and high voltage cell with 3D oxide-structured spinel. The GEN4 (2025–2030) will focus to commercial deploy of solid state batteries.

A schematization usually used to compare the different characteristics of lithium batteries in terms of specific energy (capacity), specific power, safety, performance, life span, and cost is realized via radar diagrams (higher value is better) and shown in Fig. 4 (Miao et al. 2019).

Nickel batteries are generally less energy efficient than Li-ion batteries, but they perform well at high current rates. They are also safer and more robust, which makes their control systems cheaper (i.e. they don't need balancing). The main technology currently developed is:

Nickel-metal-hydride (Ni-MH): they use hydrogen alloys and are common in portable devices. They offer good energy density and C-rate. However, they are heavier and bulkier than Li-ion batteries. Their main advantage is that they don't form dendrites, reducing the risk of overheating and internal short circuits.

Sodium Batteries base their popularity on the abundance and low cost of their main material. Several technologies, mainly divided into low temperature and high temperature sodium batteries, are currently developed. The main technologies with potential use in building are:

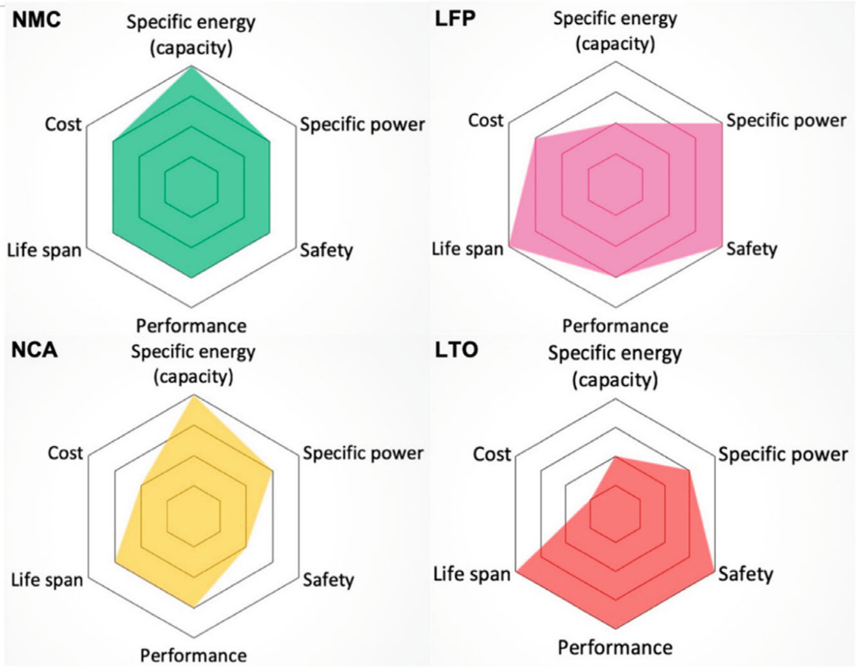

Fig. 4 Radar diagrams to compare different lithium batteries for building applications (Miao et al. 2019)

Sodium ion (low-temp): considered the heirs of lithium-ion, are appearing on the market with different manufacturing process. They feature a lower energy density (probably reaching LFP one) but high interests in research sector could fill the gap. They are safer and cost-effective, offering high C-rate and good lifetime.

Sodium-nickel-chloride (high-temp, $NaNiCl_2$): they operate at high temperatures (270–350 °C) and involve a charging process where nickel and salt transform into molten sodium and nickel chloride. They have a long life cycle and high energy density but require significant thermal management.

ZEBRA cells: they use iron chloride, nickel chloride, or a mix of both with molten sodium tetra chloroaluminate as electrode material. They are safer, less corrosive, and operate over a wider temperature range than other high temperature batteries such as sodium-sulfur batteries. They have a long life cycle (2500–4500 cycles) (Solyali et al. 2022).

Some technologies ($Na–O_2$, $Na–CO_2$) show good performance at the small-scale level, nevertheless, further development activities are needed to improve sodium anodes technology. Sodium-ion based batteries will become widely diffused in next years and also solid state device can improve performance and safety (Wu et al. 2024).

All the technologies previously explained are suitable for small size systems (i.e. below 50 kW). A family that is arousing interest in stationary applications are the Flow Batteries. They are particularly attractive due their capacity to be designed separating the energy content, which depends on the tanks' size, from the power released, which depends on stack size. Electro-active materials (held in tanks) constitute two redox couple solutions. By pumping through the stack, energy exchange can occur. They offer long life cycle, low-maintenance and deep discharge. However overall efficiency is lower than other technologies. Normally they are inserted in larger systems (hundreds ok kW and more), given that the cost depends a lot on the various systems needed for operation. Main technologies developed are:

Zinc-based flow batteries (Zn/Cl_2 or Zn/Br_2): they offer high energy and power density, low environmental impact and low price, gaining popularity among batteries. The main drawbacks are efficiency and volume used for minimum power release.

Vanadium redox batteries (VRBs): they store energy through electron transfer between different ionic states of vanadium. They are known for their long-duration energy storage capabilities, high power release and quick time response. Low energy density and high costs are the main limits.

Polysulfide bromide (PSB) flow batteries: they use a reversible electrochemical reaction between sodium bromide and sodium polysulfide. A polymer membrane separates the electrolytes, allowing sodium cations to transfer between electrodes. PSB batteries are known for their quick response time, high energy efficiency and low environmental impact. High preparation cost is the main challenge for diffuse commercialization.

All the technologies briefly explained show different advantages and disadvantages with Li-ion technology leading the sector. Their main role in power to x economy is to make renewable electricity to become the primary energy source (Breyer et al. 2024). In addition, the flexibility offered by fast response, high C-rate and high efficiency storage system can enable optimized management of the electricity used, allowing price-based behaviors and demand response (DR) programs (Xu et al. 2022). Some works in literature show the importance given by the electricity storage system to implement efficient decision-making power-to-x technologies able to manage uncertainties and variability of these systems (Burre et al. 2020). In particular, at building level, the combination and integration of renewables, batteries, heat pump and/or thermal storage is very interesting. In (Baraskar et al. 2024) how smart control strategies can optimize heat pump operation to reach higher and better self-consumption is highlighted. Some management algorithms were developed and validated using some key performance Indicators (KPIs), showing that seasonal performance factor (SPF) is improved. It practically describes the benefit related to a reduced grid electricity need to meet the household heating demands. In REACT project (Freeman and Coakley 2021), heat pump systems and energy storage combined use (properly shifting when heating or cooling energy is used) enables demand-side management or demand-response strategies. Three paths, using electrical or thermal storage, are possible to manage electricity and heat in buildings and different use strategies and challenges were explored inside this project. The work in (Palomba et al. 2021) explores more in detail the realization and control of hybrid thermal/electrical storage system coupled with heat pump. The system was characterized and studied to improve efficiency and lifetime in a specific use case. Hybridized storage will be further explained in the following section.

2.3 Hybrid Energy Storage + Power-To-X

The definition of hybrid storage is wide, covering the integration of different electric storage technologies (e.g., batteries and supercapacitors (Anta et al. 2024)), electric and mechanical storages (e.g., batteries and flywheels (Li et al. 2024)), electric and chemical storages (e.g., batteries and hydrogen (Jacob et al. 2018)). This paragraph focuses on the analysis of the existing examples of hybrid storages dedicated to the electric and thermal provision to buildings. Indeed, this hybridization approach is considered extremely urgent, taking into account the route towards the decarbonization of buildings (European Commission 2022). Actually, overall, the building sector still represents around 40% of energy consumption in Europe with a large portion of it caused by heating and cooling demand (UNEP 2024).

In this context, most of the reported papers in the literature are focusing on the optimization of the joint operation between electric and thermal storages, using a numerical model approach. For example, Mehrjerdi and Rakhshanib (2019) proposed a hybrid model for an energy storage system integrating both thermal and electrical storage within a building, in which both thermal and electrical loads are modeled using Gaussian probability distributions, considering ideal electrochemical and thermal energy storage systems with a certain efficiency and charge/discharge power (i.e. regardless of the technology). The electric energy supply was provided by the electrical grid, and the goal was to minimize daily energy costs through the optimal operation of the hybrid storage system. Scenario-based stochastic modeling was employed to address the uncertainty in load forecasting. The obtained results showed that the electrical storage system can reduce costs by approximately 15%, and the thermal storage system reduced costs by around 17%, and the coordinated hybrid thermal-electrical storage system can cut costs by about 34%, resulting in the most effective way to integrate energy storage in buildings. Dong et al. (2023) investigated the role of hybrid energy storage, including electric, hydrogen and thermal provision, to support rooftop photovoltaic (PV) operation on a building. A generic model for electric energy storage is used, whereas the thermal energy storage model is based on a water tank. The numerical modelling investigation and optimization demonstrated that the overall integrated system can achieve an annual return on investment of 36.37% and a levelized cost of energy of $0.1016 per kWh. Moreover, it can reduce the annual carbon emissions by 25.5 tons compared to a system with only rooftop PV + electrochemical energy storage. This confirmed the potential of hybrid energy storage solutions to mitigate the stress on the local grid by reducing the peak power needed. Another example, by Brandt et al. (2022) focused on the development of a simplified method to optimize the sizing of hybrid battery/TES systems. The analysis highlighted that integrating batteries with a TES system enhances the system's load-shaving capacity by 20% compared to a system with only electrochemical energy storage. At the same time, hybrid energy storage improves the economics of the system, thanks to the lower capital cost of the TES against the battery, allowing for a reduction of annual expenses in the range of 10 000–60 000 $. Moreover, in the case of climatic zones with high cooling demand, the hybrid solution is always more efficient than the standalone battery or TES system since it increases the available discharge power by up to 40%.

The above reported analysis highlights the huge potential of hybrid storage solutions in buildings, especially when coupled with onsite renewables and innovative heating and cooling provision devices (e.g. heat pumps). Nevertheless, most of these analyses are using standard storage technologies, marking a lack of experimental activities dedicated to the development of novel components, able to maximize the integration of hybrid thermal/electric storages both from the hardware and controlling point of view. In the following, an example of innovative solutions for heating, cooling and power storage and provision in single-family buildings is presented, to highlight also the need of innovative technological packages to make hybrid storages competitive for future market uptake.

3 Description of a Fully Integrated Hybrid Solution for Buildings Integration: The HYBUILD Solution

Within the EU-funded project HYBUILD (Cordis web page 2017), an innovative system to produce heating, domestic hot water (DHW), and cooling was developed for Continental (only heating and DHW) and Mediterranean (including cooling) climates. Most important is that the system included sensible, latent, and electrical energy storage, to increase the use of renewable energy on-site (one of the main KPIs targeted). Moreover, this system integrates a three-media refrigerant/phase change material (PCM)/water heat exchanger in a heat pump using a low GWP refrigerant, R32.

3.1 HYBUILD Solution for Continental Climate

The Continental solution was developed for a multi-family house (MFH) located in Stuttgart (Germany), as being representative of the building typology for the building stock in Continental climate regions in Europe. The innovative system for this Continental climate is shown in Fig. 5. The main components of the system are a PV system connected to the heat pump, ten sensible heat storage DHW storage tanks

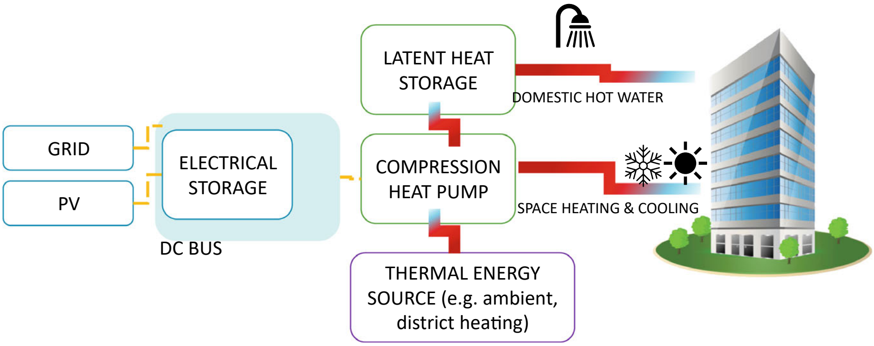

Fig. 5 Schematic diagram of the innovative hybrid system for the continental climate

(one for each dwelling), a high-temperature latent heat storage tank, and a Lithium-Titanate-Oxide electrochemical energy storage system. The latent heat storage, which employs a commercial paraffinic material, is connected to the compressor outlet to store part of the energy contained in the hot refrigerant gas that leaves the compressor, which is used to generate DHW in an efficient way. There are many innovative aspects in the proposed system, such as the direct integration of an innovative three-media refrigerant/PCM/water heat exchanger (RPW-HEX) in the hot superheated section of the heat pump, the use of electric storage combined with both sensible and latent heat storage, and the use of a DC microgrid and innovative control for coupling the electric grid with the thermal distribution. Therefore, the use of PV panels and both the thermal and electrical storage systems help increasing the share of renewable energy.

The sizing of the main components of the system was as follows. The PV system nominal power and the electrical storage capacity were calculated with an iterative process to ensure that 40% yearly self-consumption and self-sufficiency were ensured, therefore 10 kWp of PV peak power and 15 kWh of electrical storage capacity (battery) were used. The water tank (sensible heat storage) was fixed according to the technology provider to 140 L. The heat pump had 30 kW nominal heating power to ensure coverage of building space heating peak demand. Finally, 80 kg of PCM were used to maximize its contribution to the domestic hot water (DHW) production.

The energy consumption of the building was calculated via dynamic simulations with TRNSYS (Klein et al. 1979) simulating each system component using standard or specifically developed types or performance maps provided by the manufacturer or developed experimentally. The annual energy consumption of the different components of the system was 6374 kWh/year for the heat pump, 3654 kWh/year for the electric heater, 658 kWh/year for the fan coil, and 392 kWh/year for the circulation pumps, with a total of 11,078 kWh (Llantoy et al. 2021).

The economic performance of the full system was assessed (Emhofer et al. 2020). The systems showed a payback time of 12.4 year with energy savings of 622 $\mathrm{kWh_{el}}$

per year. That analysis also showed that this system is best suited for low-energy buildings in cold climates.

The environmental performance was also assessed using the life cycle assessment (LCA) methodology using both the ReCiPe and IPCC GWP indicators. For the Continental system, results showed that the overall impact (measured with both indicators) of the innovative system is lower than that of the reference system. The impact for the operational stage (manufacturing stage and disposal stage) is higher than that of the reference system, but the lower impact during the operational stage compensates for it (Llantoy et al. 2021). The analysis of the subsystems considered shows that the sensible heat storage and the PV panels are the subsystems with the higher impact (34% higher and 30% higher, respectively), while the high-temperature latent TES storage subsystem has a contribution of 20%. Finally, the other two subsystems considered have the lowest impact contribution, with 10% the electrical storage and 6% the compression heat pump.

3.2 HYBUILD Solution for the Mediterranean Climate

The Mediterranean solution was developed for a single-family house (SFH) located in Athens (Grece), as being representative of the building typology for the building stock in Mediterranean climate regions in Europe. The innovative system for this Mediterranean climate is shown Fig. 6. The main components of the system are a field of lineal Fresnel solar collectors and a PV system to increase the use of renewable energy sources. To improve the energy efficiency of the heat pump working in cooling mode, a sorption chiller is used in cascade with the heat pump. The heat produced by the Fresnel collectors is used to drive the sorption chiller in summer, but it is also used to contribute to the energy supply for heating and DHW to the building. In addition, the system incorporates a low temperature PCM thermal energy storage tank and an electric battery to help increase the energy efficiency of the system.

The sizing of the main components of the system was as follows. The PV system nominal power and the electrical storage capacity were calculated giving 20.9 m^2 of PV panels and 7.3 kWh of electrical storage capacity (battery). The water tank (sensible heat storage) was fixed according to the technology provider to 800 L fed with 60 m^2 of Fresnel solar collectors. The heat pump had 13.2 kW nominal cooling power to ensure coverage of building space cooling peak demand with a cooling storage capacity of 12 kWh of PCM storage. Finally, the DHW tank had 250 L.

Again, the annual energy consumption of the system was calculated with TRNSYS. The energy consumption of the heat pump was 1564 kWh/year, for the dry cooling was 215 kWh/year, for the adsorption storage was 80 kWh/year, for the DHW electric heater was 552 kWh/year, and for the circulating pumps was 355 kWh/year, with a total annual energy consumption of 2766 kWh/year (Zsembinszki et al. 2021).

The LCA carried out using both the ReCiPe and IPCC GWP indicators showed that the overall impact (measured with both indicators) of the innovative system is

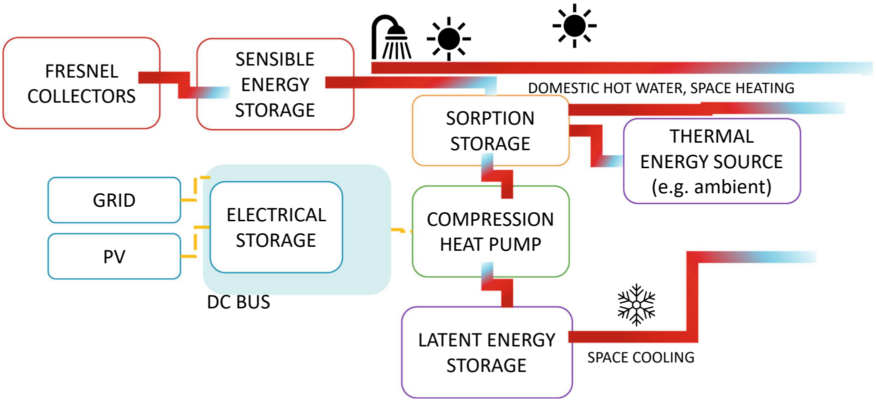

Fig. 6 Schematic diagram of the innovative hybrid system for the Mediterranean climate

higher than for the reference system, mainly due to the higher complexity of the system. Due to the lower use of electricity from the grid compared to the considered reference system, the impact during the operational stage is lower than during the manufacturing and disposal stages. So, in this case, the higher impact in manufacturing due to more components in the system is not compensated by the operational stage. When analysing the subsystems, the higher contribution in the overall impact comes from the TES system, the sorption storage, and the solar field (with 29%, 27%, and 21% contribution respectively). The other subsystems (electrical storage, heat pump, PV panels, and sensible heat storage) have a much lower contribution (14%, 7%, 1%, and 1% contribution respectively) (Zsembinszki et al. 2021).

3.3 Core Technologies

The proposed system for the Continental concept includes the following main components:

- Reversible heat pump.
- Latent heat storage.
- Electricity storage.

The reversible heat pump employs R32 refrigerant, a low-GWP refrigerant and its main peculiarity compared to the state-of-art is the use of a DC-driven compressor. Indeed, as shown in the schematics in the previous sections, the HYBUILD system includes a DC bus, for the connection of the PV, the electricity storage and the compression heat pump. Energy from the grid when local production is not available is also transmitted to the various components through the DC bus by using an AC/DC converter. This choice allows a better exploitation of the renewable energy sources on site, since it eliminates the conversion stages between the PV, the electricity storage and the heat pump.

The latent heat storage consists of the desuperheater of the heat pump, as discussed in (Emhofer et al. 2020, 2022). It is an aluminium heat exchanger with passages for three fluids: PCM, heat transfer fluid (HTF), and refrigerant. It is installed in the refrigerant line of the heat pump and uses a commercial PCM with melting point of 64 °C. The PCM is directly charged by the hot refrigerant of the heat pump and releases the heat to the heat transfer fluid, which is, in turn connected to the domestic hot water distribution system of the building. This configuration, with the latent storage embedded inside the heat pump, allows reducing the heat losses that would occur in case of transferring the heat from the refrigerant to a second fluid and then to the PCM.

The proposed system for the Mediterranean concept, instead, includes the following main components:

- Fresnel collectors.
- Reversible heat pump.
- Sorption storage.
- Latent heat storage.
- Electricity storage.

The general idea is to exploit the cascading integration of the sorption system with the vapour compression unit. The energy needed to drive the sorption unit is solar energy, which is harvested by Fresnel collectors. The peculiarity of the Fresnel collectors for the HYBUILD system, is their modularity and the possibility of being used also in small and medium-scale applications.

The sorption unit consists of two modules employing zeolite/water working pair, based on the concept patented by Fahrenheit GmbH, which allows the growth of the zeolite directly on the aluminium heat exchangers. An extensive description of the concept is given in (Velte-Schäfer et al. 2023). The main advantage of the HYBUILD sorption unit compared to other adsorption chillers on the market, is the use of the zeolite, which can operate better at high external ambient temperatures.

The cooling effect to the end-user is provided by the evaporator of the vapour compression unit. The peculiarities in the units are the cascade connection to the sorption unit and the integrated refrigerant-PCM-water heat exchanger. The cascading connection consists in the hydraulic connection of the heat transfer fluid side of the condenser of the compression chiller with the evaporator of the adsorption one. In this way, the heat from the vapour compression chiller is "pumped" to the adsorption chiller, which then discharges it to the ambient by means of a dry cooler. In this way, the condensation temperature of the vapour compression chiller is reduced compared to the ambient temperature. This allows reducing the pressure difference between evaporator and condenser in the vapour compression heat pump, limiting the energy consumption to drive the compressor. The refrigerant-PCM-water heat exchanger is extensively described in (Mselle et al. 2022a, b) and consists of an aluminium heat exchanger of the multi-port extruded tube type, in which there are three separate circuits: for the PCM, for the refrigerant of the vapour compression unit, and for the heat transfer fluid, which is used to actually deliver the cold energy produced to the user. A commercial PCM with melting point of 4 °C was selected for the purpose. It is worth mentioning that the configuration with the three fluids allows the direct integration of the storage inside the vapour compression unit, thus eliminating the needs for extra heat exchangers for their connection.

Finally, the electricity storage for both the Continental and Mediterranean concepts is based on lithium-titanate-oxide (LTO) batteries. This choice was made due to its long lifespan, which aligns with the typical lifespan of PV systems, as well as its exceptional safety—essential for building installations—and high charge and discharge C-rates. This makes it suitable for various services (both energy and power), including operation with on/off heat pumps. Specifically, during the project development, commercial batteries were employed, where the Battery Management System (BMS) was adapted, and communication interfaces were debugged to ensure full control of the storage system by the supervisor. Testing at the cell, module, and pack levels showed strong alignment with the expected specifications. In particular, tests conducted in a climatic chamber at high temperatures demonstrated excellent safety and performance, even at temperatures up to 45 °C. Lab-scale simulations under real operating conditions revealed a high self-consumption rate due to the battery storage (56–62%) and a very low average operating temperature (27 °C), ensuring safe operating conditions.

4 Case Study: HYBUILD System in Mediterranean Climate

In the following, the performed validation and demonstration campaigns for the developed hybrid storage solutions are described. The concept was firstly evaluate in the lab under controlled conditions and then installed in a demo building to analyze the seasonal operation.

4.1 Lab-Scale Validation

The system was first validated at lab-scale at CNR ITAE (Messina, Italy). The test stand with the system connected is shown in Fig. 7.

The validation was done at four different levels. First the operation of the system without the sorption module in terms of typical dynamic evolution was evaluated. Then, the cascade mode in terms of dynamic evolution was tested. Following, an overall energy balance of the system to identify the relative flows and contributions of the components to the overall energy required and supplied by the system was investigated. Finally, the performance maps of the system for the various operating

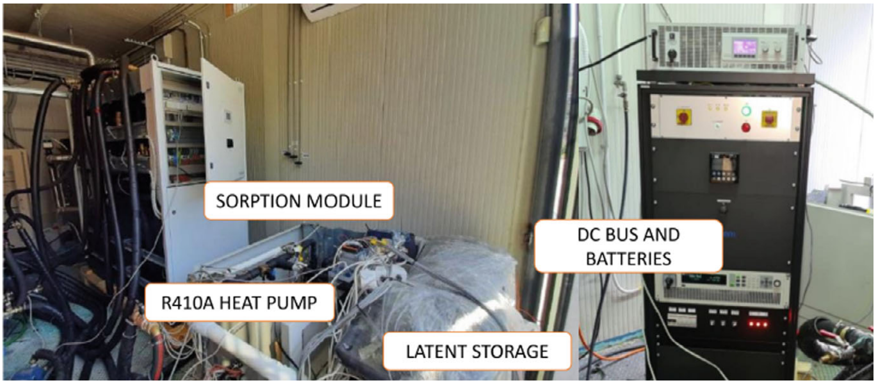

Fig. 7 HYBUILD system installed at CNR ITAE lab (Palomba et al. 2021)

modes as a function of boundary temperatures in the different circuits was calculated. All the results are presented in Palomba et al. (2021); here only a summary is included.

The test without the sorption module were carried out to calculate the electricity consumption of the vapour compression heat pump while charging the latent heat storage at different ambient temperatures, as well as to evaluate the time needed to charge and discharge the storage and the correspondent energy released. The energy that the storage was able to accumulate and release was up to 1.8 kWh, with an average EER (Energy Efficiency Ratio) of the compression heat pump in the range of 3–4. The cascade operation includes, instead, the combination of the sorption storage + compression heat pump + latent heat storage. In this case, the energy efficiency of the heat pump increased and, to achieve the same cooling effect, an EER of 4–7 was measured.

Figure 8 shows the thermal (top) and electric (bottom) powers measured during a test in cascade mode. It is possible to notice the typical cyclic behaviour of the adsorption unit. The behaviour of the compression unit (see as an example the power at the compressor, purple line) is also partly following the oscillations of the sorption unit, due to their cascade coupling. The cooling power at the evaporator of the compressor unit is always in the range of 5–7 kW, with an electricity consumption that is almost constant at 2 kW.

The energy balance for different operating modes is shown in Fig. 9. For consistency in comparison, identical boundary conditions were applied: inlet medium temperature for the sorption module ($MT_{in,sorp}$) or for the compression module ($MT_{in,comp}$) was set at 33 °C, with an inlet high-temperature source (HT_{in}) of 85 °C and an outlet low-temperature target ($LT_{out,comp}$) of 5 °C. A comparison of the first operating mode (charging latent storage) with the parallel charge/discharge mode reveals that approximately one-third of the total evaporation heat is stored in the phase change material (PCM) during parallel charge/discharge operations, while the relative electricity consumption remains unchanged. Similarly, for the charge of the latent storage and the parallel charge/discharge of the latent storage in cascade mode,

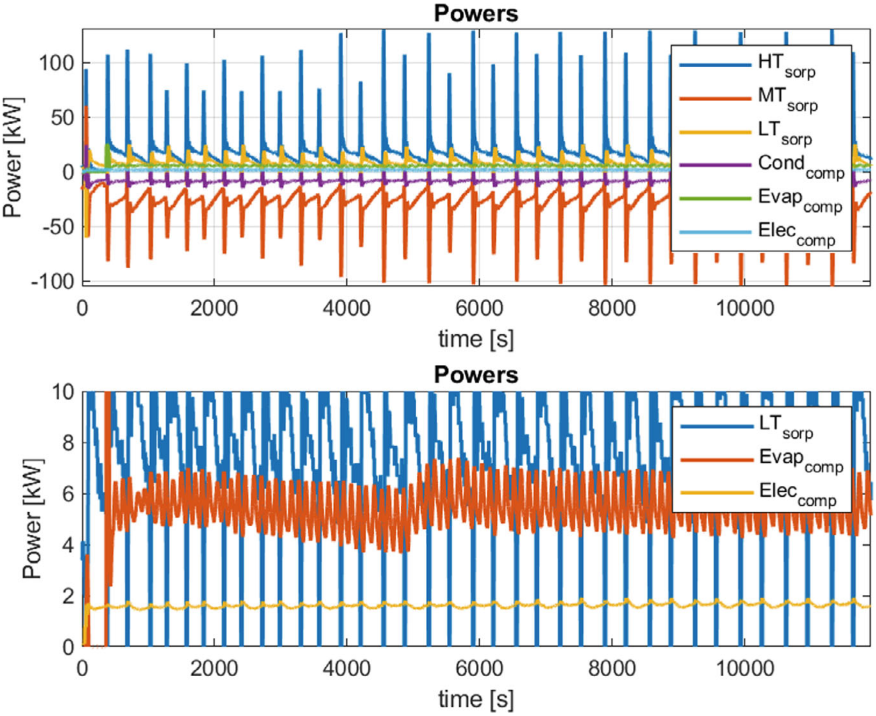

Fig. 8 Example of power in the various components for the HYBUILD Mediterranean concept during lab tests: on top all the powers measured in the prototype, at the bottom a detail of the cooling generation. HT_sorp stands for thermal power driving the adsorption module; MT_sorp stands for thermal power rejected to the ambient by the adsorption module; LT_sorp stands for the cooling power delivered by the evaporator of the adsorption module, cooling down the condenser power of the electric chiller (Cond_comp); Evap_comp stands for the cooling power delivered by the electric chiller; Elec_comp stands for the electric consumption of the electric chiller

the findings indicate that about two-thirds of the overall cooling effect is delivered directly to the user, with the remaining portion of the evaporation heat stored in the PCM. Generally, under these operating conditions, the system achieves a heat input to cooling effect ratio of 3:1, while the compression unit demonstrates an electrical efficiency exceeding 3.

4.2 Demo Implementation

The system described was implemented in a two-floors single-family house, located at Almatret (Lleida, Spain) and built in 1970. Minor renovation was carried out in 2014, replacing windows, blinds and balcony doors to improve their thermal performance. The building serves as medical office and the second floor has a residential

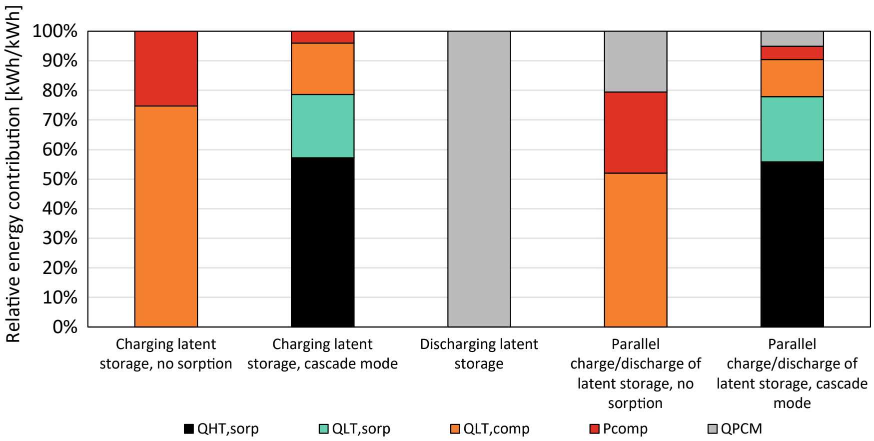

Fig. 9 Energy balance of the HYBUILD Mediterranean concept during lab tests

purpose, where the doctor family lives. The tested system serves the heating and cooling demand of the first floor. This first floor has 8 rooms, with a gross area of 132.5 m^2 and a net/heated area of 112.5 m^2. At the time of the system implementation, the house was heated with a propane gas boiler, and there was no air conditioning system. The main aim of the new system was to provide comfort conditioning during Summer, using the available solar energy. The estimated yearly space cooling demand is around 2600 kWh and the cooling peak power 3 kW (Rossi et al. 2021).

The hybrid multi-energy system tested at Almatret is based in the diagram illustrated in Fig. 5, integrating different components, including 6 modules of Fresnel solar collectors equivalent to 60 m^2 of mirrors surface are, 14 monocrystalline PV panels covering an area of 28 m^2 and providing a total power output of 5.74 kW$_p$, a sorption chiller connected to a dry cooler, a standard heat pump working with R410A refrigerant, modified to allow the integration of a PCM tank working as evaporator (with RT4 PCM with a nominal melting temperature of 4 °C), a gas boiler working as back-up, a 800 L buffer tank storing the water coming from the Fresnel solar collectors and being used as heat source for the sorption chiller, a DHW tank, an electric battery installed on an electric rack, and connection to the power grid via a DC bus. The system is designed for combined heating, cooling, and DHW production, utilizing renewable energy sources and storage for optimized building energy performance. The components are shown in Fig. 10. The installation was equipped with the required sensors to be able to monitor the performance of the system.

The first evaluated results were the harvested solar energy with the Fresnel solar collectors and the daily accumulated heat flows to the DHW tank, the sorption chiller, and the buffer tank (including ambient heat losses) (Fig. 11). Results show very different behaviour in the different days evaluated, due to sun availability and cooling demand. When the sorption is not active (i.e., the first two days), only about 20% of

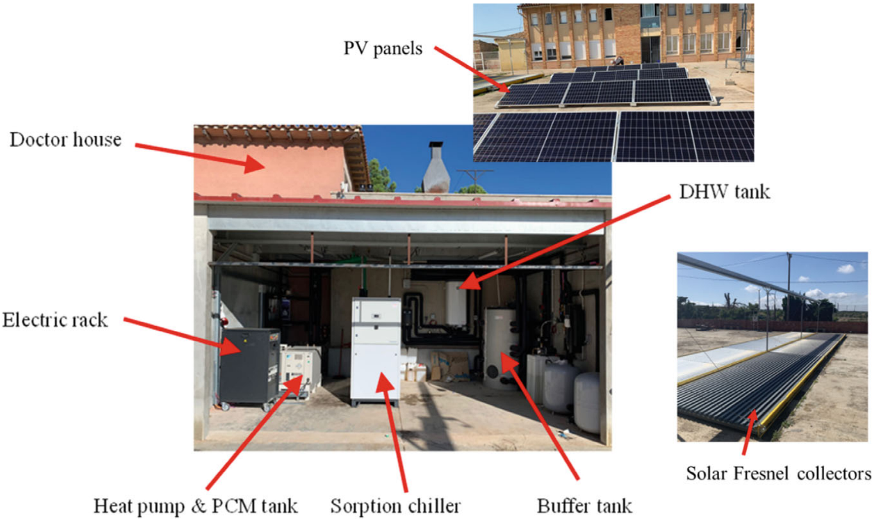

Fig. 10 Demo site located at Almatret (Lleida, Spain). Adapted from (Zsembinszki et al. 2024)

the harvested solar energy is used for DHW. When cooling is needed, around 65% of the energy produced is used by the sorption system (Day 3).

The assessment over a full season was done using the thermal seasonal energy efficiency ratio ($SEER_{th}$) and the thermal seasonal performance factor (SPF_{th}). Experimental results from Almatret (Spain) gave a $SEER_{th}$ of 0.35 while the numerical simulations of a theoretical model in Athens (Greece) gave a $SEER_{th}$ of 0.57. On the other hand, the experimental SPF_{th} was five times higher than the theoretical one.

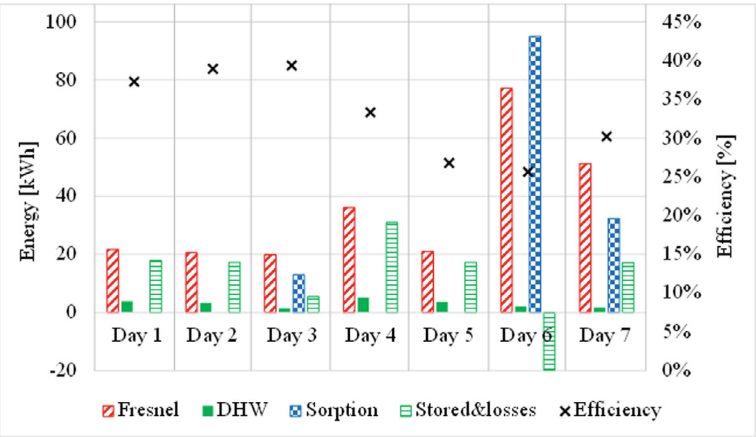

Fig. 11 Harvested thermal solar energy and heat flows in the system up to the buffer tank (Zsembinszki et al. 2024)

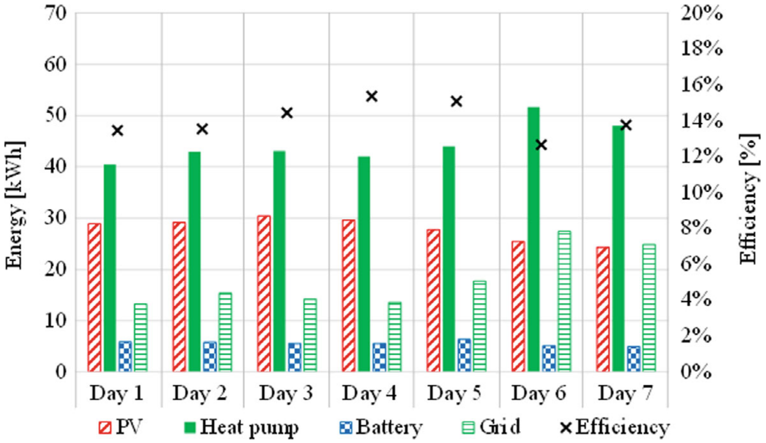

Fig. 12 Harvested electric solar energy and accumulated electricity flows (Zsembinszki et al. 2024)

Looking at the results related to electricity production and use (Fig. 12), first the PV production shows a weekly average of 28 kWh, delivering between 5 and 6 kWh to the battery.

The assessment of the full season electrical performance gives an average daily self-consumption of 0.80, higher than the 0.70 obtained theoretically. The self-sufficiency experimental result was similar to the theoretical one, around 0.50. Finally, the experimental average share of renewables was 0.67. The weekly average of the share of renewables is higher than the self-sufficiency, as expected, due to the contribution of the renewable fraction of the power grid.

5 Lessons Learned and Recommendation for Future Development

The deployment of hybrid energy storage solutions in buildings can help in increasing the exploitation of onsite renewables to support the decarbonization of the building stock. Most of the investigations in this field aimed at analysing the optimal integration of electric and thermal storages through numerical analyses, leveraging on existing standard battery and thermal storage technologies.

The EU-funded HYBUILD project aimed at moving one step further in this sector, by coupling innovative management strategies with new storage components development. The investigation performed both at lab-level and in a real building environment demonstrated that the developed concept is able to promote a PV self-consumption up to 0.8, with self-sufficiency of 0.5 and share of renewables for heating, cooling and power generation up to 0.67. This proved the possibility of significantly reducing the non-renewable primary energy consumption. On the contrary, the integration between concentrating solar collectors and adsorption module showed some criticalities, lowering the overall performance and increasing, under some conditions, the use of dry cooler to properly operate the vapour compression heat pump.

These findings highlight the potential of combining advanced heating and cooling technologies with thermal and electrical storage and renewable energy sources to create more efficient and sustainable building energy systems. On the other hand, it has to be considered that, from the LCA point of view, the complexity of the system increases a lot the impact during the manufacturing phase, which is only partially compensated by the environmental impact during operation.

In general, this first development demonstrates the potentiality of the solution, which requires more studies in different weather conditions to optimize its year-round efficiency. Some design optimizations will be needed to reduce the manufacturing efforts and the system' complexity, to make it more appealing for future commercialization.

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