On the development of a façade-integrated solar water storage

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Abstract

The integration of active solar thermal technologies into building envelopes has recently been receiving greater attention, and has been promoted within international projects such as IEA Task 56 and Cost Action 1403. Although the façade integration of solar thermal collectors is a topic that has been debated at length, little attention has been paid to the building integration of solar water storage.

The scope of this paper is to highlight the main barriers that are experienced in the development of façade-integrated solar water storage. This activity is a part of the SunRise project that aims to develop a new unitised curtain wall element for tertiary office buildings. The façade element integrates a complete solar thermal system consisting of a solar collector, hot water storage, a radiant panel, and all the required operation components. A mock-up of the solar façade is manufactured to identify practical constructional issues. The thermal behaviour of the tank is analysed through FEM simulations and laboratory tests.

Keywords

solar active envelope systems, building integration, product development, heat storage

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1 INTRODUCTION

In recent years, the attention given to the building-integration of active solar thermal systems (BISTs) has risen. The market penetration of BISTs, however, is still low, and a greater number of market-available solutions is desired to improve the acceptability of solar envelopes and increase the amount of building loads covered by solar energy. International efforts like IEA SHC Task 56 (IEA, 2016) and Cost Action 1403 (Cost Action TU, 2013) are investigating this topic from market, technological, and energy perspectives with the aim of studying and promoting solar envelope systems.

Scientific literature highlights that BISTs suffer from technological and economical barriers (IEA, 2009) such as high investment costs and mistakes during installation that can be effectively tackled with the development of turnkey solutions and the application of prefabrication techniques (Soppelsa et al., 2016). From this perspective, R&D projects together with industry become fundamental.

As a concrete example for overcoming such limitations, the integration of a complete solar thermal system in a curtain wall element is studied within the framework of the SunRise project. This R&D collaboration with a façade manufacturer aims to design a new turnkey plug-and-play façade element that is suitable for new and retrofitted tertiary buildings. Whenever solar radiation is considered as a means to cover thermal building loads, a a Thermal Energy Storage (TES) is required for making collected heat available at times when the solar resource is not present. The heat harvested by solar façades is typically stored in the building's thermal mass or in water-based TESs.

Low-tech passive design strategies recommend exposing the building's thermal mass in order to collect solar radiation during the day and slowly release the collected heat overnight. As in the case of Trombe walls (Givoni, 1998), air-based solar concepts can be assisted by fans and dampers or can be operated on natural convection principles. The thermal capacity of building materials can be further enhanced with phase change materials (PCM) incorporated in the wall structure or mixed with the construction materials (De Gracia & Cabeza, 2015; Kolaitis et al., 2015). The thermal mass of the envelope is also exploited by Massive Solar Thermal Collectors (MSTCs) (D'Antoni & Saro, 2012), which are capacitive building envelope structures capable of removing the absorbed heat through an embedded pipe loop. MSTCs can serve water-based active solar systems for a direct or indirect use of collected heat in covering building loads.

In existing façade-integrated solar thermal systems, the collected heat can be stored in conventional water TESs that are detached from the building façade (Risholt et al., 2015; WAF, 2018). Alternatively, solar collectors and water thermal storage can be combined into a single unit, so that neither external storage nor connection pipes are needed. This energy concept has a long tradition in hot climates but continuous research (Singh, Lazarus, & Souliotis, 2016) has resulted in improved designs, such as the installation of water storage as a separate layer behind the solar collector (Sopian, Syahri, Abdullah, Othman, & Yatim, 2004), the combination of water and PCM storage (Reddy, 2007) or the merging of water storage and absorber plate in a unique tubular structure (Khalifa & Jabbar, 2010).

From this literature review, it emerges that only a limited number of concepts and solutions of building-integrated solar water storage have been developed. As a contribution for future BIST concepts, this paper aims to share the experience acquired in the development of a building-integrated water TES, considering both technological and thermal aspects. In the framework of the SunRise project, a mock-up of the solar façade that integrates such compact water TES is manufactured to identify practical constructional issues. In addition, the thermal behaviour of the TES is analysed through FEM simulations and performance tests carried out in the laboratory facilities at the Institute for Renewable Energy of Eurac Research.

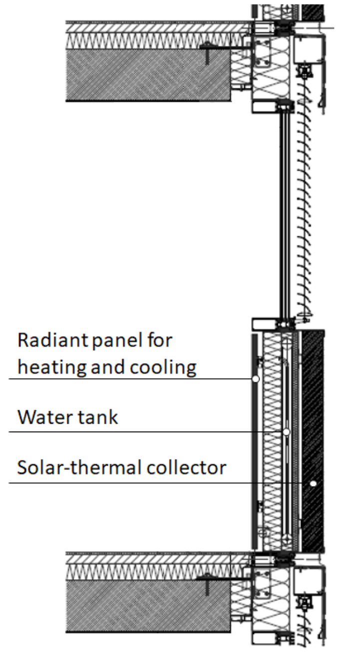

FIG. 1 Building-integration of the solar thermal system into the façade.

2 FAÇADE CONCEPT

2.1 CONCEPT OVERVIEW

The energy concept consists of a solar thermal system integrated in the opaque part of a unitised curtain wall element (Fig. 1). Such a system is composed of a flat-plate solar thermal collector installed on the external side of the façade element, a compact water TES incorporated in the parapet, and a radiant panel fixed to the inside as the finishing layer (Fig. 2). The solar system includes a hydraulic module containing the required hydronic components (i.e. circulating pump, tempering valves, expansion vessel, safety valves, fill and drain ports, deaerator, manometer, and thermometer) and an electronic board. From a construction perspective, these components are embedded within two metal semi-shells, which, once joined, guarantee air and water tightness of the spandrel panel. The solar thermal collector is hung on the external metal shell and a 3 cm air gap is left in between to facilitate installation operations.

The façade-integrated system can harvest solar radiation through the solar collector, store the collected heat in the water TES and either deliver it to the thermal zone or to a centralised DHW tank. Each façade element is equipped with two water circuits that are independent and hydraulically separated: the solar loop (SC) transfers the heat collected by the solar collector to the façade-integrated tank or to a centralised DHW tank, whereas the heating and cooling loop (HC) delivers heating/cooling power to the occupied space through the radiant panel. The heating water can be either drawn from the façade-integrated water storage or supplied by an external back-up system (i.e. gas boiler), depending on the availability of stored solar heat. The cooling water is instead produced at central system level with an auxiliary chiller and directed to the radiant panel, bypassing the TES.

FIG. 2 View from inside (left) and outside (right) of façade prototype taken during the tests in the climatic chamber.

Obviously, the development of a robust control strategy is of key importance in the effective management of heat fluxes from/to the façade, the achievement of high final energy savings, and to avoid stagnation in the solar loop. The control developed for the SunRise façade is based on an irradiance detector and a number of temperature sensors placed in the water loops and in the TES.

2.2 DRIVERS FOR THE FAÇADE CONCEPT

The development of new energy concepts should consider not only energy performance targets but all issues connected to the design, manufacture, installation, and operation of the system.
From the energy perspective, the SunRise façade concept aims:

- to cover part of heating and DHW loads through solar energy available on the external façade;
- to maximise the local exploitation of solar energy in order to reduce parasitic heat losses in distribution pipework (quantified in 20% of the collected heat (DGS, 2005));
- to share the excess collected heat at building level.

The key technological driver is the prefabrication of the hydronic circuit in order to (1) reduce construction and installation costs and (2) achieve higher quality workmanship. Prefabrication principles such as modularity and standardisation of components are prerequisites in this activity.

The façade-integration of a solar thermal system influences the layout of generation, transmission, and emission systems. The manufacturing of a façade element integrating a heating/cooling terminal allows for to savings in material costs and costs incurred during installation phases.
At building level, the installation of a decentralised TES in the building façade allows for resizing or elimination of the volume of the centralised tank and, therefore, the reduction of technical spaces. Furthermore, the thermal insulation required in the façade element could be replaced in part by the rear-side insulation of the solar collector, which could be also exploited by the tank.

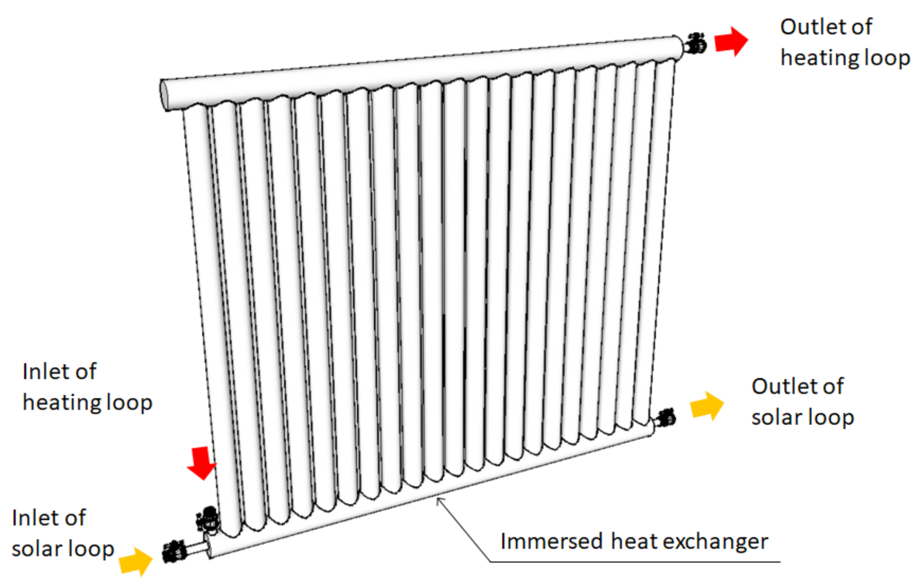

FIG. 3 Design of the TES integrated in the building façade.

2.3 SUNRISE SOLAR WATER STORAGE

The design of the TES installed in the SunRise façade is developed with consideration given to the following technological requirements:

- It has to include two independent and hydraulically separated loops.
- It must handle the thermal and mechanical stress induced by the solar system operation.
- It cannot cause detrimental conditions for the façade element.
- It has to have a minimum weight and thickness.

The SunRise storage is custom-made and consists of a series of steel cylinders connected by two headers at both ends, as shown in Fig. 3. The overall dimensions of the tank are about 1.2 m high, 1.3 m wide and 0.06 m thick for a total water capacity of about 46 litres.

An immersed heat exchanger is installed in the lower header to allow the heat transfer between SC loop and water storage. The connection with the HC loop is realised via two openings in the upper header (water outlet) and lower header (water inlet). The thermal insulation of the tank consists of a 10cm thick mineral wool layer on the inside and a 4cm thick layer on the outside.

3 CHARACTERISATION OF THE FAÇADE-INTEGRATED WATER STORAGE

The experiences gained during the product development are reported here. With respect to the façade-integration of a water TES, the analysis has a two-fold perspective: a focus on the individual component (TES) and a focus on the façade.

3.1 COMPONENT LEVEL

3.1.1 Geometry

The integration of any new component into a façade element must deal with dimensional restrictions. The overall dimensions of the tank are limited to the height of the spandrel panel, the width of the façade element, and the maximum acceptable thickness. Moreover, the building-integration of a water storage element suggests a parallelepipedal tank shape conceived as a slim flat layer inserted in the spandrel panel's multi-layer structure. The common cylindrical shape of water storage elements is hardly an option in this case because of its excessive thickness.

Another limit to the tank geometry is posed by the mechanical stress induced by the water operating pressure (in the range of 4-6 bars), which can cause structural deformations in the tank's walls and decrease its lifespan. In the SunRise façade, the tank shape is designed as the junction of more vertical cylinders so that the pressure distribution on the tank walls is homogeneous. The resistance to mechanical stress is enhanced at the price of a lower water capacity and compactness of the TES.

The energy efficiency of water storages is affected by the compactness of the tank expressed with the surface-to-volume ratio or S/V. Given a certain tank capacity, larger external surfaces mean indeed larger dispersing areas and higher heat losses. Table 1 compares the S/V ration for different shapes of TES with equal water volume. The external surface area of the SunRise TES design is about 2 and 6 times larger than for full parallelepipedal and cylindrical water storages, respectively.

The heat capacity of the TES is the result of a trade-off between tank size and the target amount of solar coverage of building loads. Insufficient heat capacity can easily worsen the performance of the whole energy system as higher heat losses through the tank walls and lower solar collector efficiencies can be expected. In the case of residential solar combi-systems, the typical design ration between TES volume and solar field area is between 40-100 L/m^2, whereas here it is limited to 18 L/m^2. In fact, geometrical constraints limit the overall dimensions of the TES and its shape further reduces the water volume to only 52% of the occupied gross volume.

Although these calculations testify a sub-optimal behaviour of the SunRise TES in terms of both heat retention and thermal capacity, thermal performance requirements were revealed to be of secondary importance with respect to geometry limitations.

TES GEOMETRY	VOLUME [L]	EXTERNAL SURFACE [m^2]	COMPACTNESS S/V [1/m]
SunRise TES	46	4.15	90
Parallelepiped		2.22	48
Cylinder		0.76	16

TABLE 1 Comparison of compactness ratio between different TES geometries.

3.1.2 Thermal insulation

Proper thermal insulation is essential for any water storage in order to reduce the heat losses through the mantle and improve the storage efficiency. When the TES is integrated in the façade, the insulating material must not only guarantee satisfying thermal performances, but also respect technological specifications such as fire resistance class and permeability to water vapour. As already pointed out, the insulation layer installed in the spandrel panel of traditional façade elements or on the back of rear-insulated solar thermal collectors can synergistically reduce the thickness of the tank insulation layer.

Different insulation thicknesses and materials (mineral wool and VIP vacuum insulation panel) are considered during the design process of the SunRise TES. In spite of the excellent thermal behaviour of VIP, its use in the SunRise mock-up is discarded because of its susceptibility to mechanical damages, the complexity of application, and the high cost of the materials used in the panel's core. Instead, the chosen insulation material is mineral wool because of its good thermal insulation proprieties, its excellent behaviour in fire, and the ease of its application.

In light of these considerations, two insulation layers of 10cm and 4cm are installed on the internal and external sides of the SunRise TES, respectively. A thicker insulation layer (10cm) is applied on the internal side in order to embed the water pipes, whereas the external layer can benefit from the insulation in the rear side of the solar thermal collector.

The heat transfer coefficients (U^{2D}) calculated with COMSOL simulations under the hypothesis of stationary conditions and bi-dimensional heat transfer are shown below (Fig. 4 and Fig. 5). The total heat losses correspond to 1.9 W/K (or 85 W for a ΔT = 45K) for the chosen configuration, that is equivalent to a class E efficiency hot-water storage according to the Commission Delegated Regulation (EU) No 812/2013. The main cause of such poor energy performance is undoubtedly the shape of the tank, which is characterised by a large heat dispersing surface per unit of volume.

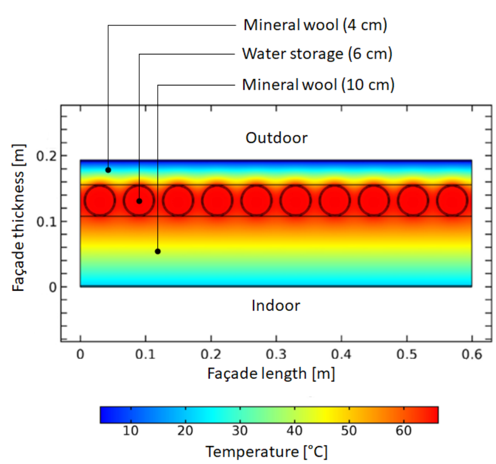

FIG. 4 FEM simulation of the TES assuming T_{water} = 65°C, T_{indoor} = 20°C, $T_{outdoor}$ = 4°C.

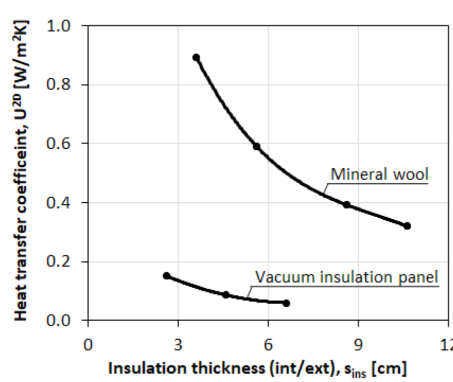

FIG. 5 Heat transfer coefficient calculated from FEM analysis for different insulation thicknesses.

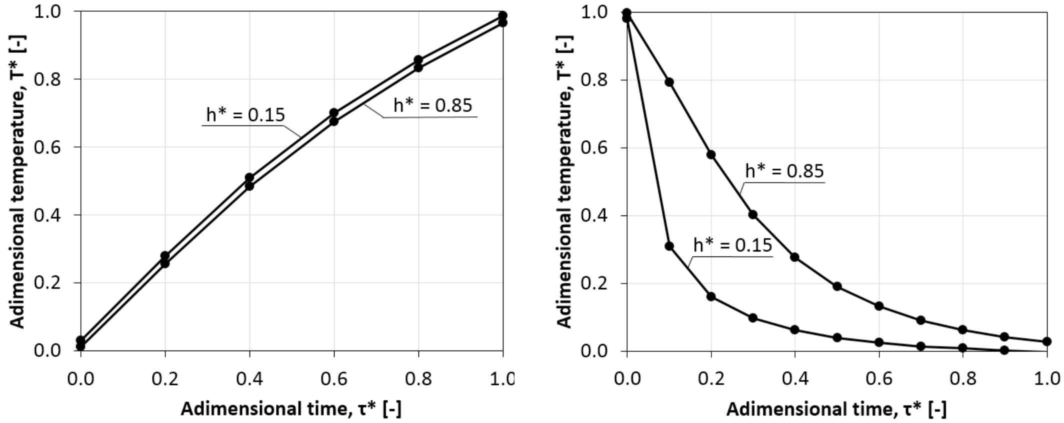

FIG. 6 Adimensional temperature in the TES during charging phase on the left (T_{min}=23.5 °C, T_{max}=76.1 °C, Δτ=5 h, H=1.2 m) and discharging phase on the right (T_{min}=21.1 °C, T_{max}=76.1 °C, Δτ=72 h, H=1.2 m).

3.1.3 Thermal stratification

The thermal stratification in TESs is beneficial to the performance of solar systems as higher solar collector efficiencies are achieved, the heat losses from equipment are reduced, and the set point temperatures for heat delivery can be more easily reached. In this perspective, a key factor in TES design is the definition of the height-to-diameter ratio of the tank. The typical recommended ratio for TES with optimum stratification is at least 2.5:1, whereas the ratio in the developed TES concept is about 20:1 and thus a good thermal stratification is expected.

Fig. 6 shows the temperature profiles of the charging (left) and discharging (right) phases measured during the experimental activities carried out in a climatic chamber. The hot and the cold chambers are kept at a constant temperature of 20°C and a sun simulator is used to provide a constant irradiance of 1000 W/m^2 on a solar collector surface during the charging test. The temperature stratification is expressed with the notion of adimensional temperature T* (=$\Delta T/\Delta T_{max}$), calculated using minimum and maximum temperature measured during the test. Temperature sensors are installed at different heights of the TES and, in particular, at a relative height h* of 0.15 and 0.85. The transient variation of temperature is expressed as function of adimensional time τ*.

The charging phase starts when the TES is at fully-mixed conditions and in thermal equilibrium with hot and cold chambers. It can be observed in Fig. 6 that fully-mixed conditions are maintained during the whole charging process as the solar heat exchanger is installed in the lower header of the SunRise TES. The test is interrupted after 5 hours when the maximum temperature of about 76°C is reached. At this point, the charging phase test is interrupted and the artificial sun is switched off. The discharging phase test consists of the monitoring of the TES temperature variation due to the sole thermal losses across storage mantle. This process is much slower than the previous one and it takes 72 hours before initial temperature conditions are restored.

3.1.4 Product availability and cost

The façade-integration of the water tank must deal with shape and technological constraints that go beyond the range of products that are commercially available, so tailored solutions have to be designed. The price per unit of volume of the tank is expected to be significantly higher with respect to the solar TES available on the market. This is due to three factors: the small size, the high rate of consumption of raw material per unit of volume, and the customisation of the product. Assuming a specific list price of €2/L that can be achieved for standard solar tanks, the target price for the SunRise storage should be less than €100, which is unrealistic at the current stage.

3.2 FAÇADE-INTEGRATION LEVEL

3.2.1 Weight and thickness of the façade

The integration of water storage into the spandrel panel undoubtedly increases the complexity of the façade in several aspects, but the most visible and straightforward effect is an increase in the weight and thickness of the façade. In the manufactured mock-up, the integration of the water storage causes an increase of the façade weight of about one quintal, of which around half is due to the weight of the steel and half is due to the weight of the water. The use of plastic materials in place of steel could reduce the overall weight, but it is not recommended because of the lower resistance to thermal and mechanical stresses. The primary and secondary load bearing structures of the façade shall be appropriately sized to account for the additional weight and prevent deformations overtime.

The thickness of the façade element is increased by the integration of the TES in the layered structure of the spandrel panel. Such effect, however, is relatively limited when a slim parallelepipedal tank is installed, as in the case of the SunRise TES that is only 6 cm thick. The need for thermal insulation in addition to that already installed also increases the weight and the overall thickness of the façade.

3.2.2 Heat fluxes

When the façade-integrated tank is charged, a fraction of the stored heat is progressively lost over time through the tank walls. The heat losses can be reduced improving the insulation quality, increasing the insulation thickness, decreasing the external surfaces and minimising thermal bridges. A fraction of heat losses is directed to the inside and can affect the indoor microclimate. In particular, parasitic losses from TES can be considered a beneficial side effect during the heating season: the temperature of the zone slightly rises, the user comfort is improved and the active heat transfer from space heating terminals can be reduced. If this phenomenon is beneficial during the winter season, in summer it represents an undesirable event that shall be avoided as much as possible since it might cause an increase of space cooling energy demand. The magnitude of heat losses is affected by the water temperature in the storage element and thus also by the heat capacity of the water storage and the typology of solar thermal collector (unglazed, glazed, or evacuated tube).

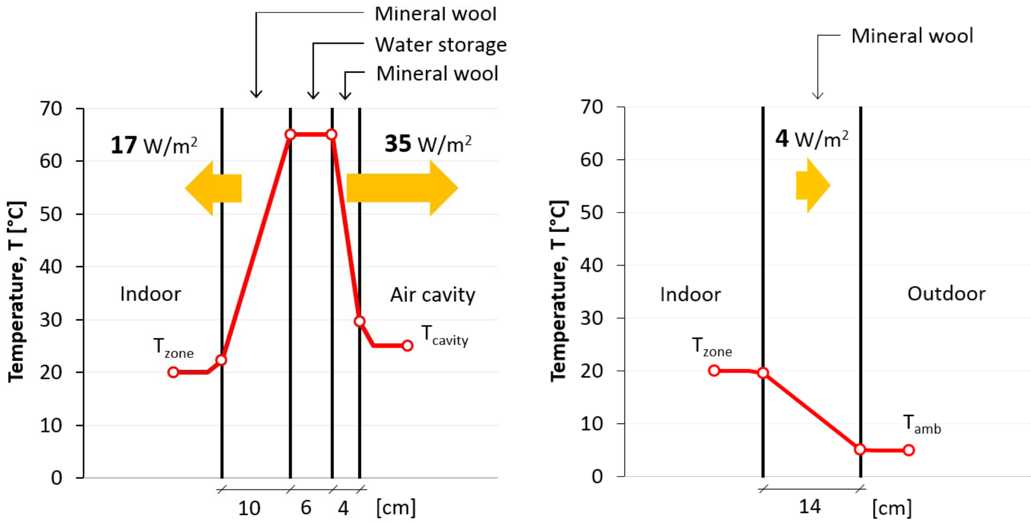

FIG. 7 Comparison of temperature gradient and heat fluxes under between the façade-integrated TES (left) and an insulated assembly (right) during the winter season (T_{zone}=20°C, T_{amb}=5°C, T_{cavity}=25°C).

The heat losses from the front and rear sides of the charged tank are compared in Fig. 7 against a traditional façade construction with the same insulation thickness (14cm of mineral wool) and identical boundary temperatures (indoor: T_{zone}=20°C, outdoor: T_{amb}=5°C). The calculation is performed considering a mono-dimensional heat transfer model and stationary conditions. The façade-integrated solution is assumed to be adjacent to an air cavity at 25°C (average temperature measured during solar collector operation). As can be observed, the heat flux is directed outwards in case of the traditional façade assembly, whereas the thermal losses of the TES represent a heat gain for the thermal zone for the solar active façade.

3.2.3 Hydraulic layout of the façade element

The installation of the TES in the façade element increases the complexity of the façade and, therefore, the requirement for inspections and maintenance as well as the risk of failure. Hydronic components such as an expansion vessel, valves, and charging and discharging points might be required depending on the design of the hydraulic system. The SunRise solar façade is designed so that the solar field can be enlarged by connecting multiple façade elements to each other with limited design efforts since a single hydraulic module can serve up to 10 solar façade elements. This is possible through a number of water pipes embedded in the façade thickness that pass through the mullion and a set of throttles that ease the connection between adjacent façade elements.

3.2.4 Accessibility to the stored solar heat

The exploitation of the stored solar heat can be limited in case of façade-integrated tanks, as some services such as DHW preparation are centralised. Viewed from a broader perspective, the interaction between façade-integrated solar thermal collectors and heating distribution networks can be easily realised if a central water storage is installed. In this case, the solar thermal collectors might cover not only the space heating demand of the zone nearby the installation site, but also other thermal loads of the building (i.e. DHW).

4 CONCLUSIONS

The paper reviews the development process of a façade-integrated solar water storage. This activity is carried out within the framework of an R&D project where the scope is the development of a new solar envelope system for the tertiary building sector. During the project, a mock-up of the façade concept is manufactured, simulated, and tested in the climatic chamber of the Institute for Renewable Energy of Eurac Research (Bolzano, Italy).

From the project activites, it emerges that the integration of a solar water storages is not an easy task. Looking at the SunRise façade development, the respect of the technological requirements and the achievement of high thermal performances are difficult goals to attain at the same time. Moreover, as the solution is building-integrated, geometrical requirements (i.e. thickness, compactness) drive the development of the façade concept and play a much more relevant role than energy efficiency criteria.

More specifically, the façade-integration of the TES binds its design to geometrical limits that are unfavourable to the purpose of heat storing. The overall dimensions are constrained and the high surface-to-volume ratio is responsible for higher thermal losses compared to traditional shapes. The design of the thermal insulation of the tank is also restricted in terms of thickness and material properties by the façade structure. In addition, such tanks are not available on the market and therefore must be customised at higher costs. Focusing instead on the façade-integration, the overall thickness and weight of the façade elements are increased by the addition of the water tank. Parasitic heat fluxes toward the interior are expected to occur, with a positive fallout during the heating season and a negative one during the cooling season. Finally, the accessibility of the stored solar heat is limited by the delocalisation of the stored heat and integration of central services or thermal loads could be difficult without an additional central tank.

Although the results are not so encouraging, the experience gained is considered highly valuable and can set new design drivers and incentives for future developments on solar envelope systems.

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