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Façade-integrated massive solar-thermal collectors combined with long-term underground heat storage for space heating

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Abstract

This work shows how façades of industrial buildings can be used as a heat source for a heat pump heating system. Opaque sections of the building skin are formed by façade-integrated massive solar-thermal collectors (FMSC) in order to collect solar radiation and heat from the ambient air. By means of a building-integrated long-term storage (BLTS), the heat collected during the summer period is conserved for utilization during the heating season. Depending on the current ambient conditions and the actual heat demand, different operating modes are to be applied: In part load with favorable external conditions the space heating demand is covered by direct use of the FMSC heat output. With rising heat demand and lower heat gain from ambient, heating is accomplished by a heat pump with FMSC or BLTS as heat source. With regard to architectural restrictions, FMSC surfaces have to be operated at temperatures above the dew point, avoiding formation of condensate or frost at the building surface. The performance of the system is modeled by means of TRNSYS, relying to available model types for the system components. The model of the core component, i.e. the FMSC, has been validated by a laboratory measurement. A design study has been carried out for an industrial building with a foot print of 1,300 m² and an annual heating demand of 82,000 kWh. Key aspect of the investigation is the identification of the most efficient system composition, characterized by the required size of collector area and heat storage volume.

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Keywords: Solar energy; building integration; energetic façades; heat pump; underground storage;

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1. Introduction

Within this publication a novel solar-thermal space heating system is presented, comprising façade integrated massive solar thermal collectors (FMSC) and a building integrated long-term thermal energy storage (BLTS). Heating energy for the building is provided by an electrically driven heat pump resorting to FMSC and BLTS as sources of renewable low-temperature ambient heat. In former installations either a heat pump has been coupled to a FMSC serving as the ambient heat source [1-3], or a seasonal heat storage has been loaded by solar thermal heat from conventional solar collectors [4-6]. Whereas, the joint application of FMSC and BLTS has not yet been realized and investigated. Long-term energy storages may serve for heat supply to a plurality of users via a district heating network or to individual dwellings [7-8].

The novel heating system shall feature the following characteristics:

- synergistic integration of heat storage and building
- synergistic integration of solar collector and building façade
- increased energetic use of the building envelop by thermal activation of the façade.
- alternative to conventional geothermal installations: thermal use of the underground, independent from geothermal boundary conditions
- no permission for the geothermal use of the underground required
- independent from given local situation
- increased efficiency of the heat pump, resulting from elevated heat source temperature provided by a long-term heat storage.
- sufficient availability of low-grade ambient heat guaranteed by the use of a long-term heat storage.

1.1. Façade-integrated massive solar-thermal collector

An effective way for implementation of FMSC is the construction of pre-fabricated façade elements, as described by [1]. A solid concrete plate constitutes the structural basis, which is covered by a thermal insulation in order to minimize thermal losses of the façade element. The outer skin of the sandwich element is formed by the FMSC. It consists of a second concrete layer equipped with a tube meander allowing for thermal activation. This outer shell is mechanically linked to the inner load carrying construction by steel anchoring rods. This punctual connection of the outer and inner shell fulfills the structural requirements with only limited influence on the thermal behavior of the massive solar collector.

The heat carrier tube is completely embedded in the outer concrete layer, respecting all technological requirements with regard to the stability of the building element and the function and durability of the steel reinforcement. Thus, FMSC allow for perfect architectural integration of solar thermal collectors, as discussed by [9]. Even as a part of a complex façade design, a FMSC element is not distinguished from a thermally inactive façade section, as long as there are no visible changes of the outer surface induced by the thermal activation. This might happen when condensate or frost is formed on the outer skin due to an extensive extraction of heat, as shown by [1]. Of course such operational states have to be avoided by appropriate control of the solar collector system in order not to disturb the optical appearance of the building.

Regarding the vertical orientation of the façade-integrated collectors, a reduction of the solar thermal yield by about 30% has to be expected as compared to a roof-top installation with optimal inclination [10]. Yet, this reduced efficiency is acceptable, since façade area is used which conventionally does not contribute to the energy supply of the building.

A water/glycol mixture is circulated through a tube register incorporated in the FMSC. When the temperature of the outer shell of the building is higher than the temperature of the fluid, heat is extracted from the FMSC. The temperature of the solar collector is governed by the thermal balance comprising radiative exchange and heat transfer. An exhaustive discussion is found in [11]. The absorber surface of the FMSC receives solar radiation $\dot{Q}^{+}_{\mathrm{rad,s}}$ and long-wave radiation $\dot{Q}^{+}_{\mathrm{rad,l}}$ emitted by the sky and surrounding surfaces Simultaneously the FMSC acts as infrared emitter releasing the long-wave radiation $\dot{Q}^{-}_{\mathrm{rad,l}}$ according to its surface temperature. Governed by this surface temperature, also exchange of sensible heat $\dot{Q}^{+/-}_{\mathrm{air,sens}}$ by means of convective heat transfer takes place. In addition, latent heat $\dot{Q}^{+}_{\mathrm{air,lat}}$ is transferred to the FMSC by condensation of humidity present in the ambient air if the temperature of the air in contact with the FMSC surface drops below the dew point. A second effect of latent heat occurs when a wet FMSC surface is dried by solar radiation, resulting in a retarded and reduced increase of the temperature of the solar collector. This phenomenon has not been taken into account by [11] and it may be of minor importance if a wetting of the surface is avoided by the roof overhang. For the sake of completeness, it is included in the following balance. Yet, due to the absence of appropriate data the drying effect of the façade is not considered within the study presented in this publication. Taking into account all involved heat portions the amount of useful heat $\dot{Q}_{\mathrm{u,1}}$ transferred to the heat carrier fluid is given by:

$$\dot{Q}_{\mathrm{u,1}} = \underbrace{\dot{Q}^{+}_{\mathrm{rad,s}} + \dot{Q}^{+}_{\mathrm{rad,l}} + \dot{Q}^{+}_{\mathrm{air,sens}} + \dot{Q}^{+}_{\mathrm{air,lat}}}_{\dot{Q}^{+}_{\mathrm{tot}}} + \underbrace{\dot{Q}^{-}_{\mathrm{rad,l}} + \dot{Q}^{-}_{\mathrm{air,sens}} + \dot{Q}^{-}_{\mathrm{air,lat}}}_{\dot{Q}^{-}_{\mathrm{tot}}} \tag{1}$$

The heat provided by the FMSC can be used by a heat pump, allowing for operation of the solar collector with low temperature and increased thermal output. The heat pump serves for the required temperature lift as given by the building heating system. In direct contact to a FMSC, a stable operation of the heat pump is accomplished [12], resulting from the large thermal inertia of the concrete layer. A second positive aspect is the limited driving temperature difference between the FMSC surface and the heat carrier, which is a consequence of the decent thermal conductivity of the concrete.

1.2. Building-integrated long-term storage

Resorting to conventional solutions, different options are available for the provision of ambient heat to the heat pump: Air, ground water and bore holes or horizontal collectors can be used. For a given case, one of these options could be chosen. In all cases, the performance of the system would be governed by the temperature level of the heat source, resulting in more efficient operation when elevated heat source temperature is available.

As an alternative to the conventional use of a heat pump, solar heat input from a FMSC shall be used as ambient heat source for the heat pump. Yet, for periods when the solar thermal system does not provide sufficient heat input to the heat pump, an alternative heat source is required as backup. Thus, a long-term heat storage has been chosen as backup heat source for the heat pump. The heat storage is realized according to the established water-gravel storage design as described by [4]. Heat input and output is accomplished through a closed heat carrier loop. During summer and in periods of low heat demand of the building the storage can be regenerated by heat input from the FMSC. In this way, surplus heat collected during the summer is buffered for use during the heating period. With regard to the annual operation and the desired high storage efficiency, an efficient thermal insulation of the storage envelope is required in order to minimize thermal losses.

As discussed by [13], a gravel-water heat storage can serve as supporting structure, allowing for positioning the storage underneath the building. With this integration, no additional ground floor in the surrounding of the building is occupied. And, if the storage is formed by a closed solid shell no specific building permit is required and independency from local circumstances is assured. In this way, the BLTS concept offers efficient long-term energy storage and synergistic integration of energy system and building structure. The compact geometric layout is in particular attractive for application in the commercial and industrial environment.

1.3. The heating system

Within a research project in cooperation with an industrial partner, a building energy system comprising FMSC and BLTS coupled with a vapor compression heat pump is developed (Fig. 1). The design of the system is discussed for the case of an industrial production facility. During summer, heat generated by the FMSC is buffered in the BLTS. In heating operation, the heat supplied by the FMSC is either fed to the evaporator of the heat pump or is directly transferred to the building, in case the temperature level of the solar system is sufficiently high. The BLTS can also directly provide heat for the space heating system. Yet, the main purpose is the heat supply to the heat pump.

With regard to the use of two heat sources, i.e. FMSC and BLTS, the core aspect of this investigation is the dimensioning of these two system components. For the FMSC, not only the overall size but also the allocation of the collector area to the East, West and South facing façades has to be found.

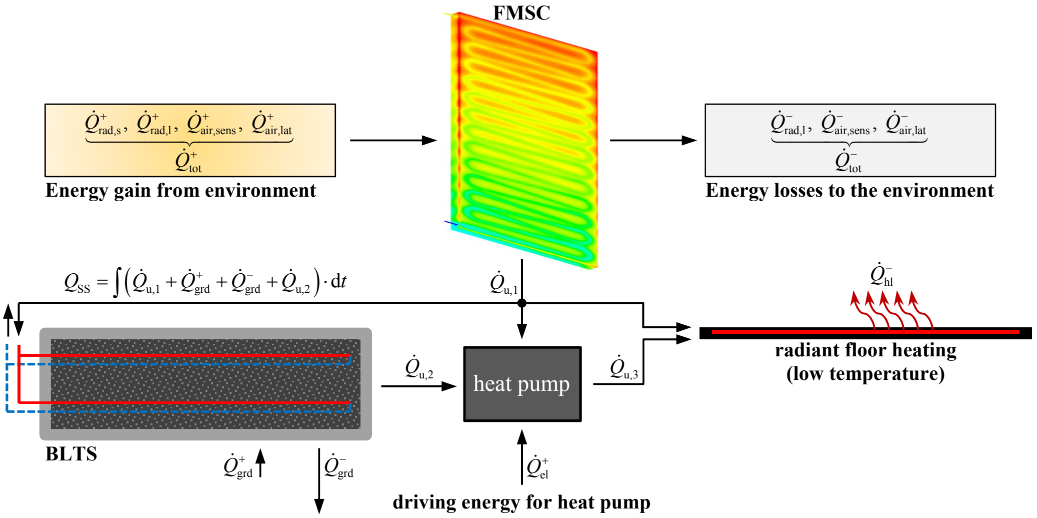

Fig. 1. System concept and thermal balance for FMSC in combination with BLTS and heat pump

Nomenclature

A	Area	[m^2]
COP	Coefficient of Performance	[–]
Q	Energy	[J]
$\dot{Q}$	Power	[W]
T	Temperature	[°C]; [K]
t	Time	[s]
σ	Stefan-Boltzmann constant	[W/(m^2 K^4)]

Superscripts

+	Gain
-	Loss

Subscripts

air	Air
el	Electric
grd	Ground
H	Heat
hl	Heating load
in	Inlet
l	Long-wave
lat	Latent
n	Normed
out	Outlet
rad	Radiation
ref	Reference
s	Short-wave
SS	Seasonal storage
sens	Sensible
sim	Simulated
sky	Sky
sol	Solar
tot	Total
u	Useable

2. Materials and methods

In this section, the applied methodology is presented and the used tools are introduced. All calculations are performed with the modeling software TRNSYS [14] using commonly available component models, so-called types, for the building and the heating system.

2.1. Building

The investigation has been carried out for an industrial building (Fig. 2) with technical data specified in table 1. For the climatic conditions in southeastern Germany characterized by the test reference year 13 (TRY13), a total annual heating demand of about 82,000 kWh has been found. In the calculations, the heating period is predefined from October 1st to April 30th. During the remaining summer period, space heating is out of operation and only BLTS loading is active.

Table 1. Building design parameter

Parameter	Value	Unit
Set temperature zone 1 (1,500 m^2; 14,400 m^3)	17	[°C]
Set temperature zone 2 (60 m^2; 180 m^3)	20	[°C]
Set temperature zone 3 (65 m^2; 190 m^3)	24	[°C]
Building height	10.5	[m]
Building length	61.0	[m]
Building depth	26.0	[m]
Area FSMC East	276	[m^2]
Area FSMC South	249	[m^2]
Area FSMC West	409	[m^2]
Average U-value	0.3 W/(m^2 K)	[W/(m^2 K)]
Resulting yearly heating demand	82,000 kWh	[kWh]

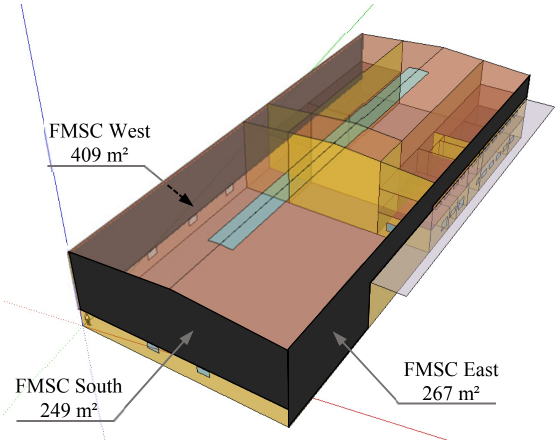

Fig. 2. 3D-representation of the industrial reference building showing the East, South and West facing FMSC

Heating of the building is accomplished by floor heating and thermal component activation; all building sections are actively heated, except the staircase and the central heating room in the basement of the building. The heating load $\dot{Q}_{\mathrm{hl,n}}$ amounts to 59.7 kW and is covered by two heat pumps. The heat pumps are installed in the central heating room in direct vicinity to the BLTS which is realized as underground heat storage, located underneath the southern half of the building. The heat pumps have been selected with 1/3 and 2/3 of the peak heating load, allowing for a cascaded operation with high efficiency in part load and full load of the heating system:

- $\dot{Q}_{H,n,1} = 28.8\ \mathrm{kW}$ (B0/W35, 5 K) $COP = 4.83$
- $\dot{Q}_{H,n,2} = 42.8\ \mathrm{kW}$ (B0/W35, 5 K) $COP = 4.60$

The rated power is based on a heat source inlet temperature of 0 °C (brine) and a heating circuit supply temperature of 35 °C. In both circuits the temperature difference between supply and return is 5 K, for operation with nominal capacity.

The thermal behavior of the building is modeled with TRNSYS type56. Special attention has been paid to the interaction between building and FMSC and BLTS, respectively. For façade sections covered by FMSC, the average collector temperature has been set as outer surface temperature in type56 for the calculation of the heat loss to the ambient. Thus, no convective heat transfer has to be taken into account for these façade sections. Analogously, losses across the ground area of the building in contact to the BLTS are modeled by the storage temperature of the first layer as ground contact temperature in type56.

2.2. Façade-integrated massive solar-thermal collector

The massive solar collector is formed by the outer shell of a concrete façade sandwich element. The design parameters of the FMSC are shown in table 2.

Table 2. Reference design parameters of FMSC

Parameter	Value	Unit
Height	2.0	[m]
Length	1.1	[m]
Thickness	0.07	[m]
Pipe outer diameter	0.012	[m]
Pipe inner diameter	0.010	[m]
Pipe position (distance from surface)	0.035	[m]
Number of pipe loops	11	[–]
Short-wave absorptance	0.78	[–]
Emissivity	0.9	[–]
Absorber thermal conductivity	2.57	[W/(m K)]
Absorber density	2,400	[kg/m^3)
Absorber specific heat capacity	880	[J/(kg K)]
Fluid	70 (water)	[vol%]
	30 (brine)	[vol%]
Fluid specific heat capacity	3,680	[J/(kg K)]

The FMSC is modeled in TRNSYS with type653. It has originally been issued to calculate floor heating systems. Nevertheless, floor heating systems and FMSC exhibit similar thermal behavior. For both components, short-wave and long-wave radiation and convective heat transfer are the dominating physical mechanisms. As a consequence, by adjusting the input variables of the type, it can be adopted for the description of FMSC.

For validation of the FMSC model, laboratory measurements have been conducted. For this purpose a sample FMSC façade element with 2.2 m^2 surface area has been produced. In order to obtain a simple geometric situation, a parallel configuration of eleven heat carrier tubes has been chosen. The tests were carried out by SPF Institute for

Solar Technology in Rapperswil, Switzerland. The validation of the FMSC model in TRNSYS refers to the following measured data:

- incident short-wave radiation
- ambient temperature
- inlet fluid flow rate
- inlet fluid temperature
- sky temperature, calculated from the incident long-wave radiation
- heat exchanger effectiveness; this value was figured out to be 0.58 for the specific setup of this FSMC and the relevant operating conditions.

As the surrounding insulation has a thickness of 0.2 m and a thermal conductivity of 0.035 W/(m K), edge and bottom losses are neglected.

On the test rig, the emitted long-wave radiation of the hot spotlights has been measured at the beginning of each test run. With these data, the effective sky temperature T_{sky} has been calculated as an input variable for type653. According to Eq. (2), T_{sky} is obtained from the measured long-wave emission $\dot{Q}_{\text{sky}}$, as given by the law of Stefan-Boltzmann:

$$T_{\text{sky}} = \sqrt[4]{\frac{\dot{Q}_{\text{sky}}}{\sigma A}} \tag{2}$$

As the test runs have been conducted with a constant fluid flow rate of 150 l/h, this value is also selected for the system simulation. Hence, with a fluid density of 1.05 kg/l the mass flow rate is 70.1 kg/(h m^2). This value is in agreement with the range of 15 to 75 kg/(h m^2), chosen by [11].

In order to obtain a simple geometric situation, a parallel configuration of the eleven heat carrier tubes has been chosen for the sample FMSC. Consequently, the flow rate passing through the single tubes is 6.20 l/(h m^2).

Finally, the heat transfer coefficient for the convective heat transfer between the FMSC surface and the surrounding air flow in dependence on the wind is calculated by type1232. For this type, the input variables are the average FMSC temperature and the wind velocity.

The results of the model validation for two test sequences of the FMSC are shown in Fig. 3. The left graph represents a test with 800 W/m^2 incident short-wave radiation and stepwise increase of the collector fluid temperature from 30 to 70 °C. The right graph reports on an experiment with a steep increase of the incident radiation from 600 to 1,000 W/m^2. For both cases, a rather good agreement of the modeling result with the experimental data is found with regard to both thermal capacity in steady state and thermal inertia of the FSMC.

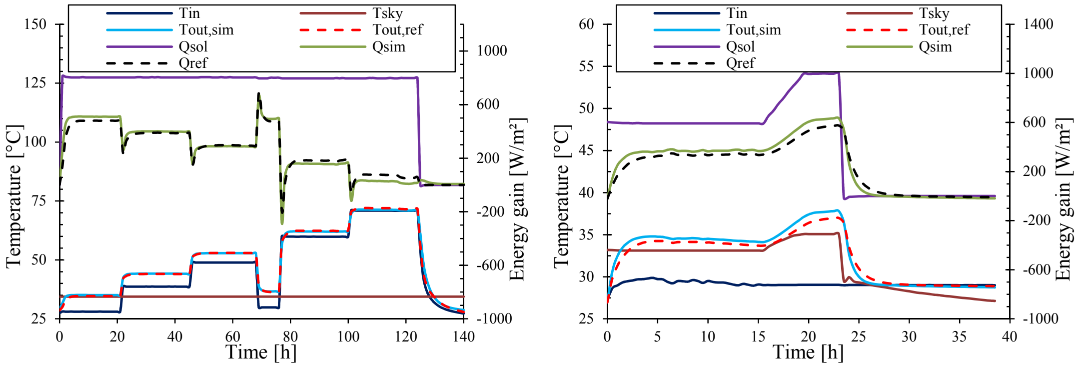

Fig. 3. FMSC reference modeled in TRNSYS with Type653. Left: Stepwise increase of collector inlet temperature. Right: Continuous increase of short-wave radiation.

2.3. Building-integrated long-term storage

The BLTS is modeled by the ICEPIT model in TRNSYS. The corresponding type343 has already been used for seasonal gravel-water storages in the German cities Stuttgart [15] and Chemnitz [16].

For all BLTS configurations investigated in the course of the case study the storage height has been set to 2.50 m. Two horizontal pipe layers with identical fluid flow are used for the heat transfer to the heat storage. According to the mode of operation, the flow rate depends either on the number of active heat pumps or on the active size of the FMSC providing solar heat to the BLTS. For heat pump 1 and 2, the flow rate is 4,200 l/h and 6,500 l/h, respectively. If both are in operation, the fluid flow is increased to 10,700 l/h.

Commonly, natural soil material is used as filling of gravel-water heat storages. However, to increase the maximum heat capacity, an alternative material is selected: broken saturated electric furnace slag. It is a waste product of smelting iron and distributed by Max Aicher GmbH named as EloMinit. The thermal properties for a mixture of coarse and fine grain under water-saturated conditions and for maximum compression are presented in table 3. For the EloMinit material a volumetric thermal capacity of about 2,600 kJ/(m^3 K) is found. For gravel the volumetric heat capacity ranges from 1,450 to 2,400 kJ/(m^3 K) in dependence on the water content. Thus, the EloMinit filling allows for a substantial increase of the storage density in comparison to the use of gravel.

Table 3. Properties of EloMinit (8.22 vol.% water).

Parameter	Value	Unit
Thermal conductivity	ca. 0.90	[W/(m K)]
Density	2,750	[kg/m^3]
Specific heat capacity	952	[J/(kg K)]

2.4. System characteristics

The heating system has five different operating modes, see Fig. 4. Mode 1 to 4 are active in heating operation. During the summer period only mode 5 is available. The modes are hierarchically structured from 1 to 5. If operation of the prioritized mode is no longer feasible, the next lower mode is activated. The following list gives the requirements for the activation of the different operating mode:

1. Direct heating via FMSC: this mode is only active if the average FMSC temperature is greater than the necessary supply temperature of the heating system.
2. Direct heating via BLTS: This mode is only active if the average BLTS temperature is greater than the necessary supply temperature of the heating system.
3. FMSC and heat pump: This mode is restricted by the ambient dew point temperature which must be higher than the average FMSC temperature. That is necessary to avoid formation of condensate or frost on the building surface. Thus, no latent heat is used by the system.
4. BLTS and heat pump: This mode is active if the average BLTS temperature is higher than the expectable return temperature of the heat pump source, including the required temperature difference for the heat extraction from the BLTS.
5. Loading of the BLTS: This mode is active if the average FMSC temperature is greater than the average BLTS temperature.

Additionally, the BLTS temperature has to be kept above 0 °C in order to avoid freezing of the storage material. Otherwise frost heave might cause severe damage of the building structure. Within the TRNSYS simulation, the heat pump is deactivated when the average BLTS temperature in mode 4 falls below 8 °C. This set point is chosen with regard to the temperature difference for the heat extraction from the storage plus the temperature spread of the brine passing through the evaporator of the heat pump.

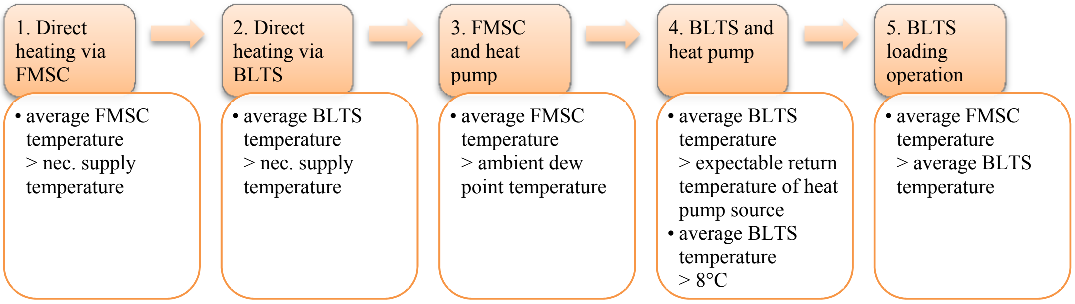

Fig. 4. System control modes. Highest priority left. 1 to 4 are only active during heating operation.

2.5. Method

At first, the solar thermal heat gain of the FMSC is simulated for East, South and West façades. As discussed earlier, formation of condensate or frost occurring at the surface of the FMSC has to be excluded. Thus, the maximum heat output of the FMSC has been estimated by setting the heat carrier inlet temperature to the dew point temperature of the ambient air. With this setting, a modeling of the annual heat output of the FMSC has been conducted.

In the second step, the volume of the BLTS is varied to identify the minimum necessary storage capacity required for covering the heating demand of the building described in table 1. The heating period starts on October 1st and ends on April 30th. During the summer months, no heat supply to the building is required and the heat gain provided by the FMSC is fed to the BLTS. During cold phases in winter time, the resulting increase of the energy content of the storage shall compensate deficits of the solar heat gain. In order to verify the functionality of the energy system with complete coverage of the heating demand throughout the entire heating period, the operation of the BLTS has been modeled for a full operational period from May 1st to April 30th. For the initial state of the BLTS on May 1st, a storage temperature of 8 °C has been chosen. This is the minimum storage temperature required at the end of the heating period which still allows covering the peak heating demand of the system. So, the target is attained if the average BLTS temperature is higher than 8 °C and if the temperature in all building zones is not falling under their set temperature.

For the ground next to the storage, the Dirichlet boundary condition is set to the mean annual ambient air temperature which is also 8 °C.

Finally, the relation between the heat output of the different façades facing East, West and South is investigated. As central result the required FMSC area in dependence on the chosen BLTS volume is determined.

3. Results

For the given setting with heat carrier supply temperature linked to the course of the ambient dew point temperature, substantial differences for the solar output of the FMSC oriented towards East, South, and West are found (c.f. Fig 5.). This fact is to be attributed to the increase of the dew point temperature during afternoon operation. Consequently, the solar gain decreases with increasing collector fluid temperature, although an equal amount of solar radiation is received by the East and West façade in the morning and afternoon, respectively.

Operated with minimal fluid temperature, in total the FMSC surfaces at all three façades provide an annual heat output of about 113,000 kWh. With regard to the annual heating demand of the building of 82,000 kWh about 31,000 kWh excess of heat is generated. Of course, the solar heat generation decreases when higher collector temperatures occur, as it is the case during loading the BLTS in the summer period.

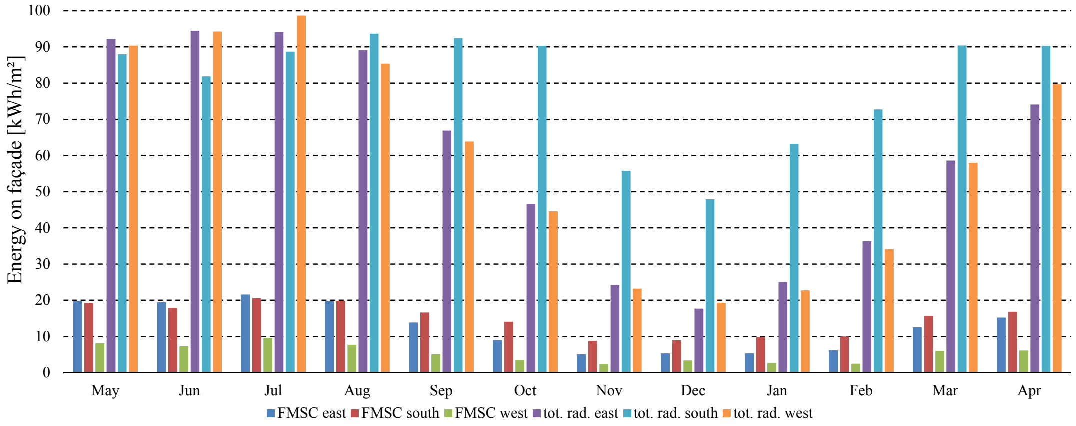

Fig. 5. Monthly energy gain provided by FMSC and total solar radiation on vertical façades. Estimation of maximum solar gain for operation with minimum collector temperature (details see text).

The result of the modeling of the energy content of the BLTS during the course of the operational year from May to April is shown in Fig. 6. When a small storage size is chosen, the storage temperature increases rapidly and stagnates when the temperature rise induces higher losses of the FMSC. This results in a reduced heat input into the BLTS. At the end of the summer period, even a decrease of the storage temperature is found due to heat loss to the surrounding underground. For larger storage dimensions, a lower temperature level of the storage is reached during summer. Nevertheless, according to the storage volume, a large amount of heat is available for the heat supply to the building during the heating period. For a small heat storage size, heat extraction beginning in October results in a rapid unloading of the storage. As there is only marginal heat gain available from the solar collector system during the winter months, a regeneration of the BLTS is not possible. Consequently, the system is not able to cover the heat demand of the building. When the storage size is increased to 7,000 m^3 or higher, the storage temperature stays above 8 °C throughout the entire heating period. This allows for reliable heat supply until the end of the heating period.

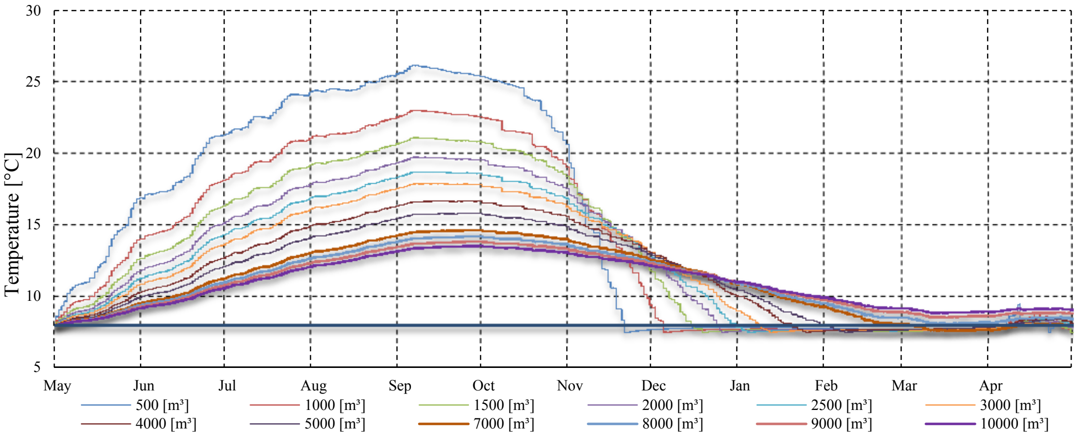

Fig. 6. Storage temperature for different BLTS sizes. Minimum storage temperature is set to 8 °C.

In addition, the increase of the annual solar gain with increasing storage size can be read from Fig. 7. Due to the lower temperature level of a large BLTS, the FMSC provides a higher annual heat output. Consequently, a lower contribution by electric energy serving as driver for the mechanical heat pump is required.

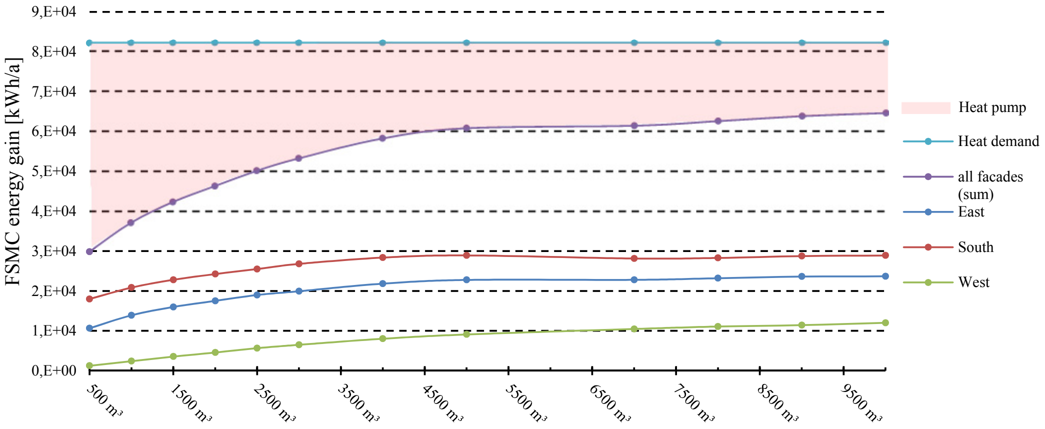

Fig. 7. Annual FMSC energy gain and heating demand of the presented building for various storage volumes

In the next step, the overall FMSC surface area is varied, keeping the ratio of the façade area facing towards South (54.4%), East and West (each 28.8%) constant. Again, the complete coverage of the annual heat demand of the building serves as key parameter indicating the functionality of the heating system. It is found that for small storage volume, a larger overall FMSC surface area is required. Yet, there is a minimum storage size which is required in order to bridge the longest cold phase during the winter period. For the given building data, at least about 2,500 m^3 are required to assure continuous operation of the heating system. In this constellation about 4,000 m^2 FSMC area are to be installed. When the storage size is increased to 5,000 m^3, a solar collector area of only 1,250 m² is sufficient, see Fig. 8.

Based on this finding, in future steps, an optimization of the system sizing can be conducted aiming at energetic efficiency and total cost of the heat supply.

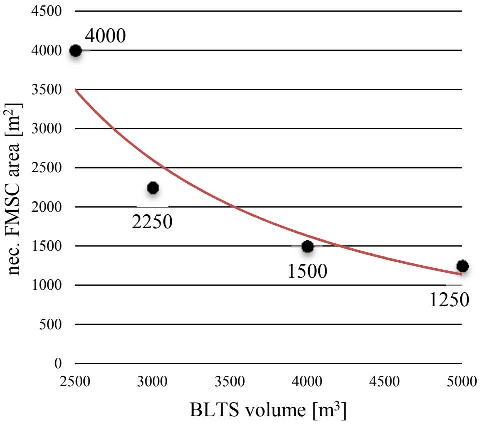

Fig. 8. Necessary FMSC area at different storage volumes. Valid for the referenced building under the given conditions.

4. Conclusion

The concept of a novel solar thermal heating system with thermally activated façade elements (FMSC) and long-term underground energy storage underneath the building (BLTS) has been presented. Operated according to a 5-staged control hierarchy, a reliable heat supply to the building is accomplished. Crucial aspect for the functionality of the system is the sizing of the core components, i.e. FMSC and BLTS. Here, a strong mutual interdependency has been found allowing for optimization of the system configuration with regard to efficiency and cost.

Further investigations will be focused on the improvement of (a) the performance and control of the solar thermal collector system and of (b) the design and operation of the long-term heat storage. Apart from the thermal design of these components, an improvement of the control strategy shall allow for increased solar gains during the heating period. A promising option is a segmentation of the heat storage and operation of the storage elements at different temperature levels. Consequently, solar gain available at low temperature level could serve for reloading a cold segment of the BLTS even during the cold period.

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