SOLAR-TILE-STOVE BASED ON PCM MATERIALS

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Abstract

The Solar Tile Stove is a completely new kind of renewable heating system that combines the traditional concept of a tile stove with the use of solar energy. In this paper we present the idea and initial measurements of a lab-scale-prototype. Furthermore, a demonstration system was installed in an existing building in Istria, Croatia. Based on extensive monitoring data we developed an effective model (Polysun) which was employed to perform annual Solar Tile Stove System simulations. Finally, we used our model to improve the system-configuration in order to achieve proper tempering of an exemplary building.

1. Introduction

Solar energy will be one of the cornerstones of the future energy mix. Besides converting sunlight into electrical energy, solar thermal systems are very well suited for meeting heating and cooling demands [1]. Especially, domestic hot water preparation is an already well-established application, whereas recently also more advanced solar thermal combi-systems for additional space heating are being employed and developed [2].
The new concept of the “Solar Tile Stove” (STS) [3] is such solar heating system that combines the traditional idea of a tile stove with the use of solar energy. In that way it is possible to retain the feature of “comfortable heat” (see Section 2) standard tile stoves are famous for.

In this paper, we first (Section 2) present the idea of the STS itself including laboratory measurements. Section 3 deals with the proof of concept within a demonstration object in Istria, Croatia. Here we show monitoring data that serve as a basis for the simulations described in the next sections. Finally, a discussion of the results and an outlook is provided.

2. The Solar Tile Stove

The Solar Tile Stove (Fig. 1) consists of a metal box which is covered by self-made ceramic tiles. These tiles are produced (for details consider www.solarkachelofen.at/) such that their infrared emissivity is very high, $\varepsilon \sim 0.9$[1]. In that way it is guaranteed that a substantial portion of the total heat is delivered by radiation, which renders tile stoves so comfortable for human beings.

In the interior of the metal box a copper heat exchanger (HEX) connected to the energy source (in our case the solar thermal system) is situated. The rest of the volume is filled with a phase change material (PCM, Rubitherm RT (paraffin)), which acts as the energy storage.

[1] We used a thermocamera in conjunction with thermocouples and a heat plate to estimate the emissivity at various temperatures. For details, we refer the reader to the corresponding author.

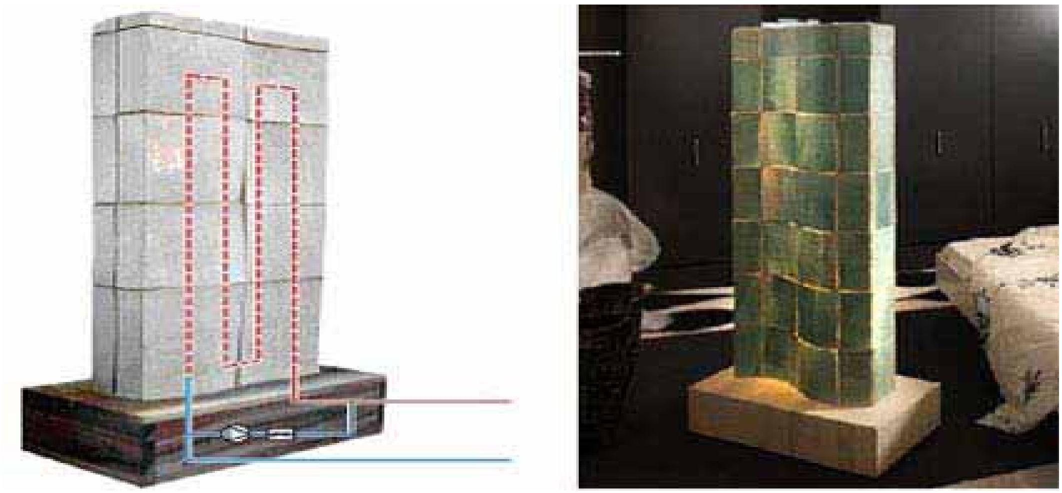

Fig. 1: Scheme of the Solar Tile Stove (STS) (left); Realization of the concept (right)

As soon as the STS is switched on, warm water enters the box, heating the paraffin. First, sensible heat is stored (the specific heat, c_p, of the solid PCM is ~ 2kJ/kg K) and subsequently the PCM is melt, whereby the heat of fusion, ΔH~150 kJ/kg, is consumed and stored.
Recently PCM materials were sought to be used as materials in thermal energy storages because of their enormous heat of fusion [4]. Nevertheless, a serious problem that was quickly identified was the difficulty of thoroughly melting larger volumes due to the very low thermal conductivity of the corresponding materials (in our case λ~0.2 W/m K), i.e. essentially the PCM insulates the HEX.

However, for the STS this physical property is actually even beneficial, in that a delay time is introduced between the absorption of energy from the solar thermal system to the delivery of heat to the building.
Fig. 2 shows various temperature profiles of an early lab-STS-prototype. An electrical heater was used to provide a certain inlet temperature and the outlet temperature, the tile-temperature and the PCM-temperature were monitored. The resulting curves show that the tiles can maintain a temperature of > 40°C[2] for a long period well after switching off the energy source.

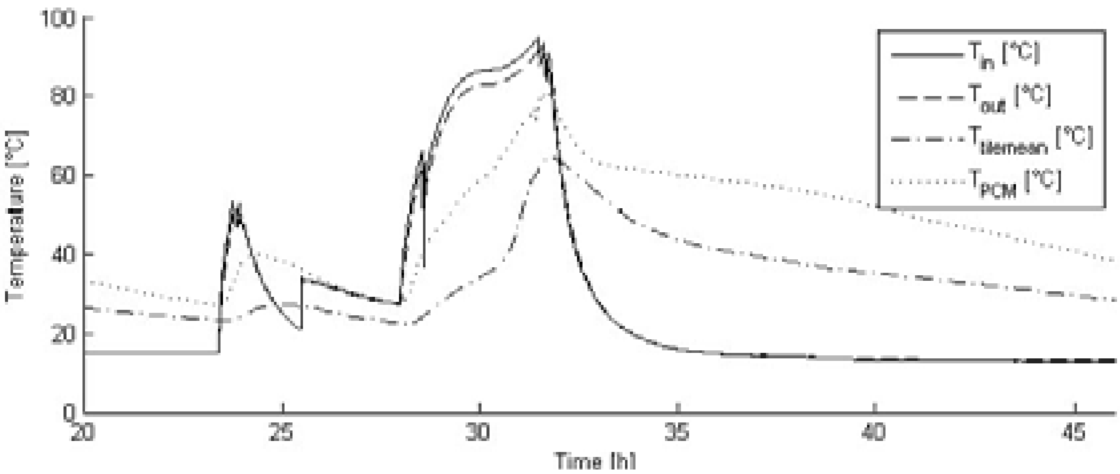

Fig. 2: Various temperature profiles for a lab-STS of 1.7 x 0.5 x 0.1 m^3

[2] Actually a higher temperature (~60°C) is even more desirable. In order to achieve that, the internal heat exchanger geometry is currently being optimized.

3. Proof of Concept – A Test-Case in Istria, Croatia

As the results of the lab-STS-tests were quite promising, the next step was to demonstrate the viability of the system-concept, i.e. to combine a real solar thermal system (collectors, pumps, optional storage, auxiliary heating) with the tile stoves and to figure out a proper way of control.

Small Solar Tile Stoves with a peak-power up to some kWs may be used in moderate climatic areas such the Mediterranean region. Especially in spring and autumn, the solar irradiation might already be enough to meet the heating demand.
In weekend-end houses, often the temperature falls rapidly during the week. The user starts heating on arrival (Friday's), but the desired temperatures are often not even achieved before departure on Sunday. Here, STS-Systems might be well suited because only one or two sunny days during the week are already enough to prevent extensive cooling of the house.

Fig. 3: Scheme of the STS-System (left); Front view of the building (right)

In order to test these potential applications, a building in Istria (CRO) was equipped with a STS-System (Fig. 3). 4 vacuum tube collectors (Rangger RS 01-15, Table 1) with a total area[3] of 9.16 m² were installed (55° tilt angle, facing to the south) to harvest the solar energy. A standard commercial pump (Wilo Star 25/6 ST) provides the volume flow and two STSs, located in two different rooms of the building, were connected in series[4]. For simplicity, the optional storage was not considered and the electrical immersion heater (auxiliary heating system) was switched off at this stage of development. We monitor the solar irradiance in the collector plane, the volume flow and various temperatures at different positions of the Solar Tile Stove System.
Fig. 4 shows curves for a typical week in spring 2010. The collector outlet temperature reaches some 80°C which leads to roughly 50°C tile temperature. The storage effect is clearly visible and heating occurs over a 24 hour-period. Consequently, the room temperatures are indeed rising such that a smooth tempering of the building is achieved.
Nevertheless, it has to be emphasized that a considerable amount of energy is due to direct solar gain in addition to the STSs (this was also confirmed by our simulations).

[3] In this paper, an area associated with a collector always means the gross area of the device.
[4] Connection in parallel may in the end proof to be more suitable.

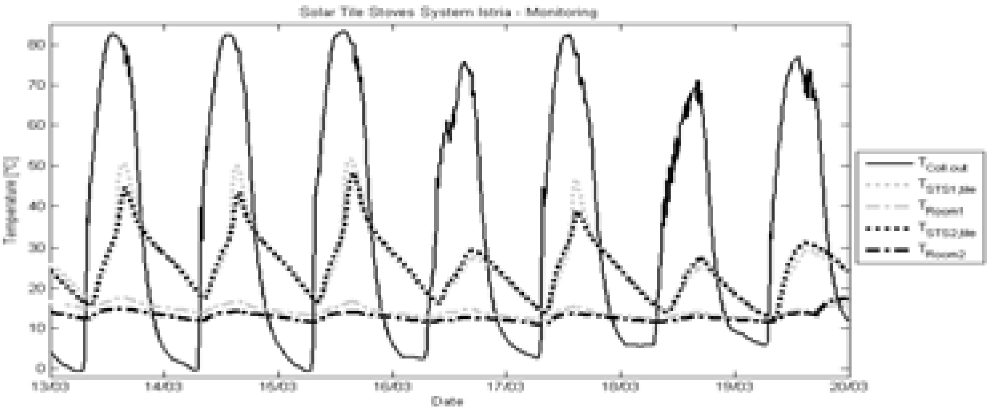

Fig. 4: Monitoring data for a typical week in March.

4. Simulation of the STS-System

4.1. Energy Analysis

Besides providing valuable insight into the workings of the STS-System, the monitoring data lay the very foundation for further improvements and also provide guidance for design and dimensioning. In order to tackle these issues a detailed analysis, model building and subsequently simulations were performed.

As a first step, we estimated the power the STSs delivered to the building. Convection and radiation are the relevant heat transfer mechanisms described by,

$$P_{rad} = A\sigma\varepsilon(T_{Tile}^4 - T_{Room}^4) \quad (1)$$

$$P_{conv} = Ah(T_{Tile} - T_{Room}) \quad (2)$$

Here $A=1.7m^2$ is the tile-covered surface area of one stove, σ = 5.6704 x 10^{-8} W/m² K^4 the Stefan-Boltzmann constant, and $\varepsilon \sim 0.9$ is the tile-emissivity. Relations for the convective heat transfer coefficient for vertical plates can be found in [5, 6].

The results of the corresponding calculation are shown in Fig. 5. A peak power of roughly 600 W per module can be expected for the very situation in March. Integration for e.g. March 16, leads to 11kWh of energy that is provided over 24 hours. One can observe that indeed a considerable amount of energy is distributed via radiation, which is a design criterion of the STS-System.

We want to emphasize here, that due to the T^4-power-law (Eqn. (1)) the fraction of heat delivered by radiation ("comfortable heat") increases disproportionate when one is able to achieve higher tile temperatures (thus more than 60°C is desirable).

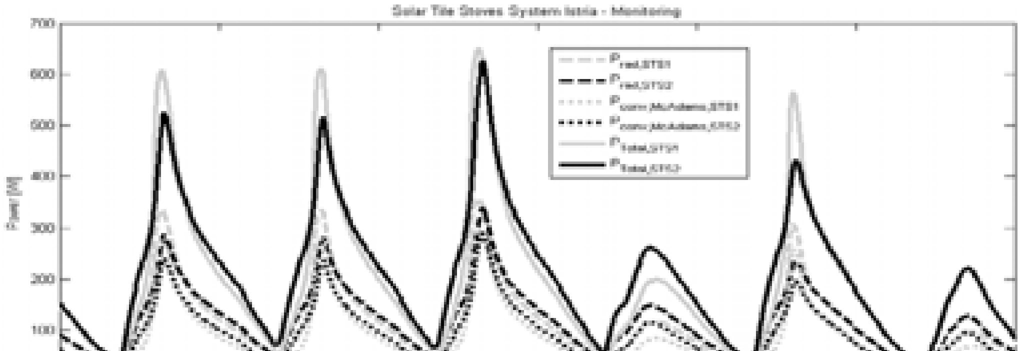

Fig. 5: Calculated radiative, convective and total power of the STSs

4.2. Modelling

The next step was to create a reasonable model of the Solar Tile Stoves that allows us to perform further investigations.
A key goal of the project was to develop a method that is useful and quickly applicable when it comes to design and dimensioning issues. Especially of interest was to identify buildings and regions where a properly dimensioned STS-System is of use. Thus, the emphasis was *not* on creating a physically sophisticated STS-model, but to develop an *effective model* that reasonably reproduces the quantities of interest (energy yield, collector temperature, room temperature, etc.).

Therefore Polysun [7] was chosen as simulation environment since it allows on the one hand easy implementation of new components (STS) and on the other hand delivers results usually within minutes.

Fig. 6 shows the Polysun-model of the STS-System. First, the collector, the piping network and the house were modelled to simulate best the monitored situation. The Solar Tile Stove itself consists of a combination of a storage (including an auxiliary pump that is switched off), a pump and a radiator.

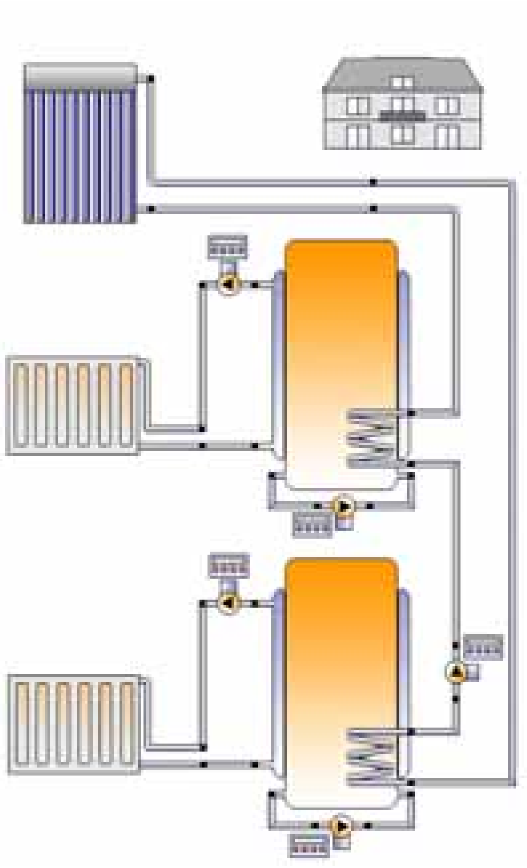

Fig. 6: Schematic of the STS-System model (Polysun)

This approach offers a bunch of variables that can be altered (storage volume, storage heat exchanger, radiator size and power, volume flow, fluid properties, etc.) to resemble the behaviour of the realistic STS. In order to determine the corresponding values, we used a representative day to "calibrate" the model, i.e. to fix all these variables.

The solar irradiation on April 28 in Polysun is similar to that of the monitoring-day April 20, 2010 (Fig. 7)[5], the simulated ambient temperatures however were somewhat lower, which might explain the differences in the collector outlet temperatures (the cooling of the solar collector during night is not modelled correctly in Polysun up to date).

By varying many different parameters of the model we were able to achieve a proper "calibration" shown in Fig 7. Although the simulation cannot perfectly reproduce the exact behaviour of the Solar Tile Stoves, which is clearly due to oversimplifications of the model, the simulated power profiles are in good qualitative agreement to the monitored ones. The total daily energy delivered to the building could be matched up to ~ 25% for the "calibration day".

[5] Although it is possible to import real weather data in Polysun, this approach was not viable because from the installed sensors it was not possible to extract all the necessary information (e.g. wind speed and diffuse radiation were not measured). However, the error that we make in comparing April 28 (simulation) to April 20 (monitoring) is negligible in view of the other simplifications of the model.

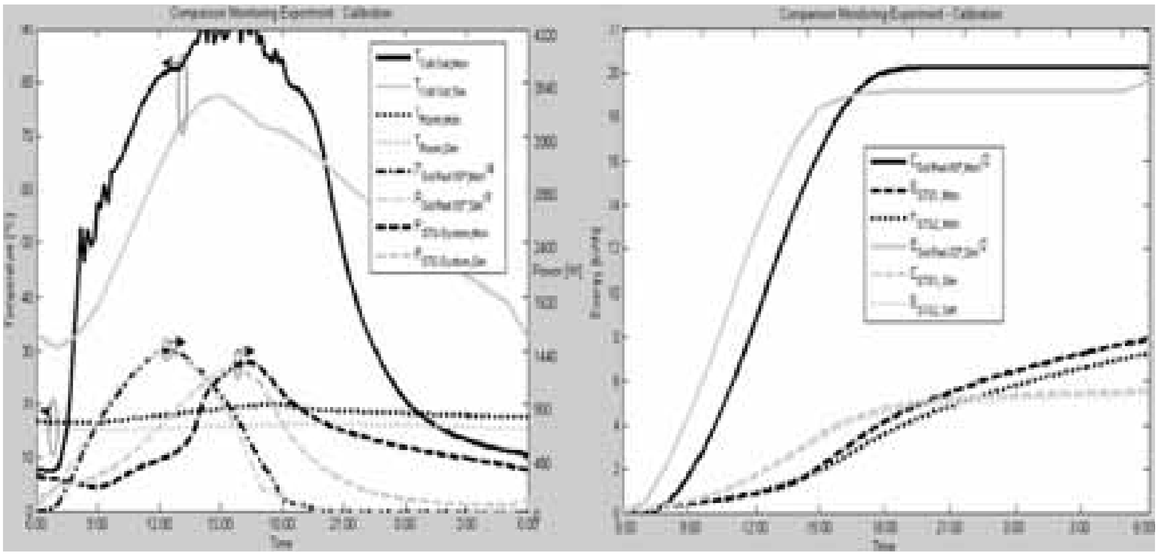

Fig. 7: Comparison of simulated and measured power and energy for the “calibration day”

4.3. Comparison between Simulation and Monitoring

In order to check the validity of our approach, we compared the simulated output to the monitored values for various days other than the “calibration day”. The results for the main quantity of interest, the total STS-heating energy, are shown in Fig. 8.

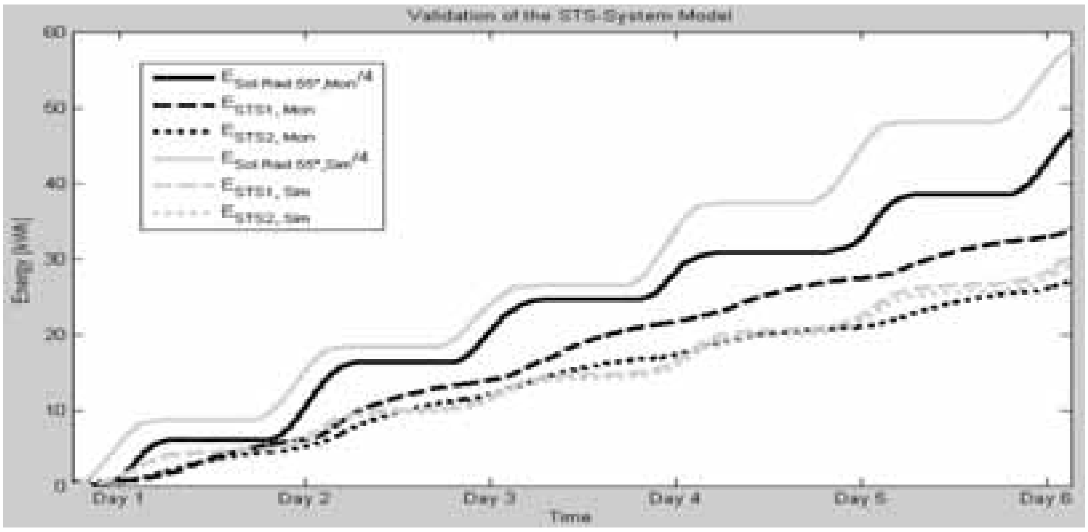

Fig. 8: Comparison of the simulated and measured total STS-energy for a period in March

Since the a primary goal of the investigations was to provide a swift design tool for dimensioning rather than an accurate physical model, the results are satisfactory.
However, it has to be concluded, that the simulations tend to underestimate the real energy to some extent. This fact should be considered when applying the model.

5. Simulation Results and Improvements

Finally, we put the STS-System model to use and performed simulations of the as-installed STS-System in Istria and an improved version.

Table 1 shows the key figures of the investigated systems located in Istria, Croatia.

	Collector characteristics	Area and U-value	Annual energy from STS-System	STS-System Efficiency
"as-installed Istria"	9.16 m² $\eta_0 = 0.66$, $a_1 = 1.8$, $a_2 = 0.005$ Vacuum Tube Collector	100 m² 1.5 W/Km²	1253 kWh	31%
"improved Istria"	12 m² $\eta_0 = 0.8$, $a_1 = 3$, $a_2 = 0.01$ Flat Plate Collector	30 m² 0.5 W/Km²	2020 kWh	26%

Table 1: Key Figures for the simulated STS-Systems in Istria

Due to the relatively low peak power of the installed prototype-Solar Tile Stoves and the bad U-Value of the building, a reasonable tempering of such a large object (7x7.2 m², 2 floors) is not possible.
In Fig. 9, this fact is highlighted for 10 days in December, where the room temperature never is able to exceed 9°C. One can expect a peak power of ~ 1kW for the two modules, which gives rise to a total energy of 1253 kWh (the STS-System is only used from October to April). This corresponds to 31% STS-System efficiency[6]

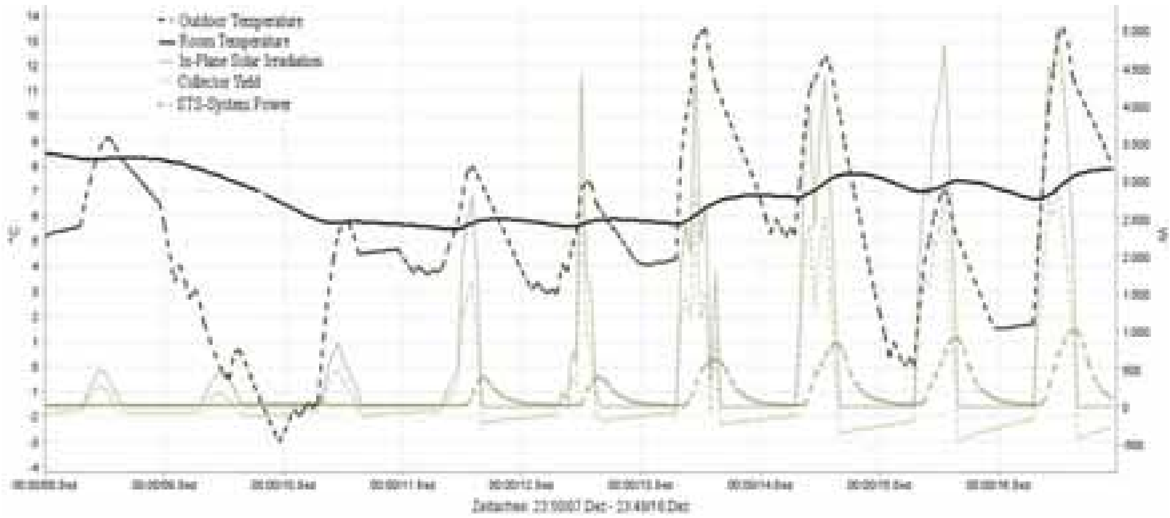

Fig.9: Simulation results for 10 days in December for the "as-installed Istria-System"

In order to estimate the potential of our small prototype-STSs, we modified the building and the solar thermal collectors (Table 1).
The improved system delivers 2020 kWh, an increase of ~ 60%. However, the efficiency is reduced somewhat which is related to the increased room temperatures (cf. Fig. 10). Even in December, the two Solar Tile Stoves have a combined peak power of roughly 2kW, which is enough to avoid total cooling of the building. Albeit not enough for a stand-alone solution, such a system is perfectly suitable for the use in weekend-houses.

[6] Here, the system efficiency is defined as the ratio of the annual solar energy in the collector plane to the energy that is delivered by the STSs for the period where the system is switched on (October to April).

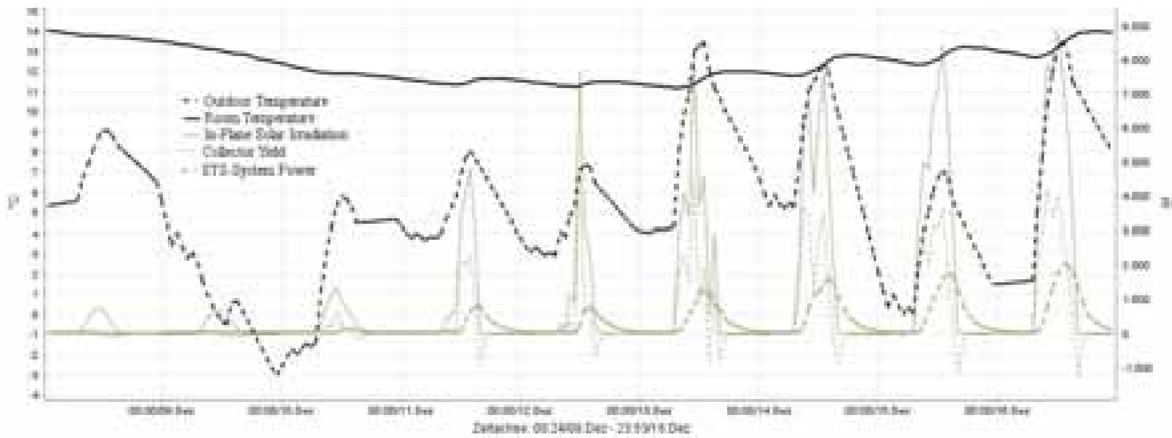

Fig.10: Simulation results for 10 days in December for the “improved Istria-System”

6. Outlook

Although, we were able to demonstrate the viability of the concept, it turned out that improvements are necessary.
On the one hand, it is clear that the heat exchanger within the Solar Tile Stove has to be optimized in order to allow for higher tile temperatures. In addition, it is necessary implement different mass flows within the collector and the Solar Tile Stove.
Also, proper dimensioning of the solar thermal collector with respect to the intended load profile is an important issue. In principle this is possible using the developed effective model. However, a sophisticated analysis and optimization is only possible with an improved physical model, which has to be implemented within a more scientific program such as TRNSYS or Modelica.

7. Conclusion

We have introduced a new kind of renewable heating system that combines the advantages of conventional tile stoves with that of solar energy. A Solar Tile Stove System was designed and demonstrated within a building in Istria, Croatia. The monitoring data proved the viability of the concept and laid the foundation for a model, which was implemented in Polysun. Our simulations lead to the improvement of the existing system in way that proper tempering of a building is possible achieving a system efficiency of 26%.

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7. Literature

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