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Simulation and evaluation of solar thermal combi systems with direct integration of solar heat into the space heating loop

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Abstract

Usually, solar heat in combi systems is used via a buffer storage. In contrast to that, the solar collectors may be connected directly to the space heating circuit in order to store the heat in the building itself. Such a direct solar integration is investigated within system simulations for different layouts and heating elements. The simulations show significant reductions in the final energy demand as well as an increasing solar yield due to less thermal losses of the storage tank compared to the usual solution with one buffer storage. A prototype of one of the investigated heating concepts within a single family house proofs the functionality of the system concept and the high solar yield, particularly at low radiation levels. Since only a few manufacturers provide such system solutions with a direct solar integration, the results may have an important impact on the future development of combi systems.

Keywords: System simulation; solar thermal combi system; direct integration; heat pump; buffer storage; floor heating;thermal activation

1. Introduction

Within solar thermal combi systems the solar heat is usually utilized via a buffer storage, see e.g. [1]. Such a storage has the advantage that the solar heat may be stored for periods without or insufficient irradiation, respectively. However, the solar yield and its effect on the end energy savings is reduced due to the necessarily higher collector temperature and the thermal losses of the storage tank. Alternatively, the solar heat may be used directly within the space heating loop. In the context of an on-going project a system with such a direct integration was developed for a

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building with a solar fraction above 50 %, where the solar heat may be used directly within a thermal activation of the concrete floor slabs. System simulations according to [2] and measured results of a test house reveal the functionality and high performance of this system. Based on this concept advanced system layouts are developed differing in the type of solar integration and the heat distribution elements. All these concepts are investigated and evaluated within a comprehensive simulation study.

Nomenclature

C	Collector
FH	Floor heating
f_{Sol}	Solar fraction
HP	Heat pump
Q	Heat amount (kWh)
Rad	Radiator
TA	Thermal activation

2. System concepts

System simulations are carried out to analyze and evaluate several solar thermal combi systems. Within these concepts the solar heat is distributed via a buffer storage and/or directly to the heat distribution elements. Integrated into a full system layout such "direct systems" are analyzed within the simulation environment TRNSYS 17 [3]. As a reference, typical combisystems with only one buffer tank are considered (named "buffer system"). Both systems may be equipped with different heat distribution elements – radiators, floor heating or thermal activation of concrete elements. The investigation also includes the aforementioned solar active house concept with a combination of two types of heating elements, a thermal activation directly heated by the solar thermal collector and radiators solely heated by the auxiliary heater via the buffer storage (named Rad + TA). All systems are shown in Fig. 1.

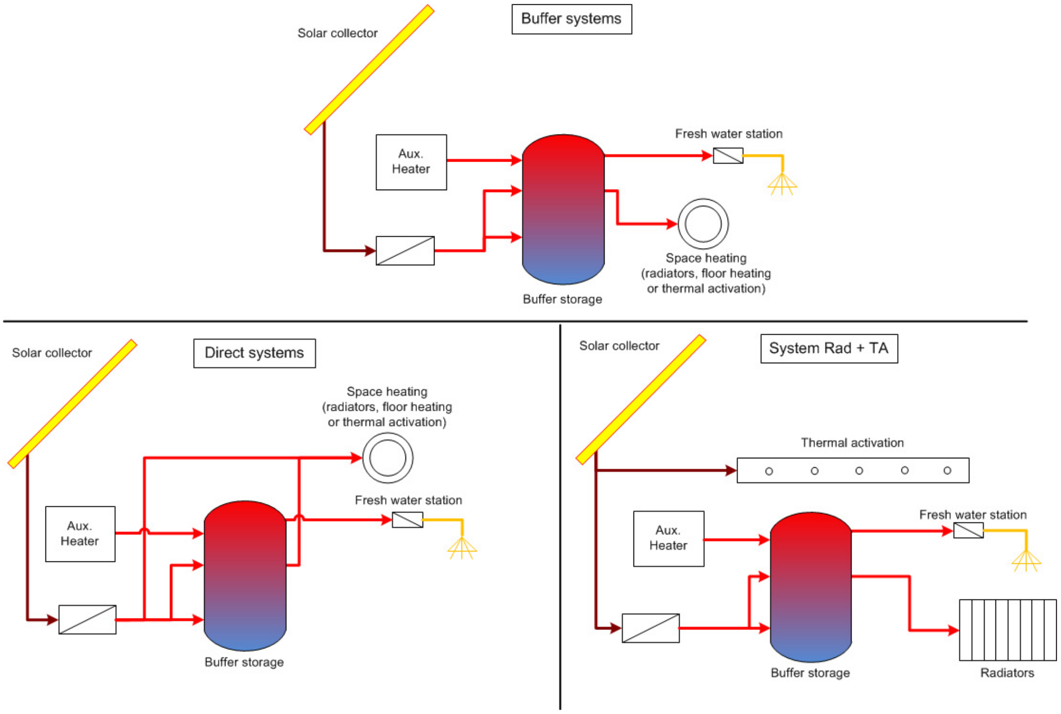

Fig. 1. Layout schemes of the systems investigated

The heat distribution elements play an important role for the evaluation of the direct solar space heating and differ in heat transfer rate, design temperature and storage capacity. Three heating elements are considered in the investigation. While radiators are heat emitters placed in the heated zones of the building, thermally activated building systems are integrated in the building structure itself. A very common form is a floor heating system (FH) where water pipes are embedded in the upper layer of the floor construction in contrast to a thermal activation (TA). Here, the piping is installed deeper in the floor e.g. in the center of the concrete. The large surface area of FH and TA allows a significantly lower operation temperature level compared to radiators which affects both the solar yield and the performance of the auxiliary heater.

Within the simulations, a heat pump and a borehole heat exchanger are used as the auxiliary heater in all systems. The heat pump is charging solely the buffer storage which is used for space heating and domestic hot water preparation. For decreasing the average condenser temperature and thus enhancing the heat pump performance, the auxiliary zone in the buffer storage is divided into two parts for domestic hot water (constant set temperature of 50 °C) and space heating (variable temperature according to the heating curve). In addition, the connection of heat pump and storage (in-/outlet heights, set temperature, sensor positions, condenser flow rate) is realized according to the recommendations of [4] to give an optimum heat pump performance.

Apart from the heat pump, the system performance is also calculated assuming a gas boiler as auxiliary heater. Alternatively to further system simulations with a boiler model, the energy consumption of such systems is calculated with the simulated auxiliary heat demand and an estimated boiler performance based on efficiency measurements carried out in the lab [5].

The control within the system decides whether the solar collector is operated and where its heat is used. In the buffer system, the solar collector is charging one heat sink, which requires only a simple on/off controller. In the system “direct solar” and the Rad + TA system the solar collector is working alternatively on two heat sinks with different temperature levels. Therefore, the controller determines the potential collector conditions for all heat sinks in advance, i.e. the conditions that would occur if the collector would charge the respective heat sink. By comparison of the potential collector outlet temperature and current heat sink temperature (e.g. temperature in the storage tank) the controller is able to decide if charging of the respective heat sink is recommended. In addition, the controller has to decide which heat sink will be used if more than one demand signal is positive. Here, the controller does not use a constant priority on one of the heat sinks. Instead, the decision bases on the potential collector output power calculated with the potential collector outlet temperatures. The solar collector charges the heat distribution elements directly, if the potential output in this mode exceeds the potential gain of the buffer storage charging by a defined factor. The optimal factor (with the lowest energy demand of the whole system) depends on the system design and has been determined with simulations for all system concepts. Details about this method are published in [6].

3. Methodology

The systems presented in Section 2 are simulated under the boundary conditions shown in Table 1.

Table 1: Boundary conditions for the simulations in TRNSYS

	Data	TRNSYS Type/Model
Location	Zurich, Switzerland	Weather data from Meteonorm [7]
Building		
Heated area	180 m^2	Type 56 [3]
Heat demand	7600 kWh/a (constant infiltration rate 0.4 h^{-1}/20 °C room temperature)	
Heat distribution elements		
Radiators	55 °C/45 °C at -14 °C ambient temperature	Type 362[8]
Floor heating	35 °C/30 °C at -14 °C ambient temperature	Active layers within Type 56
Thermal activation	27 °C/24 °C at -14 °C ambient temperature	
Domestic hot water demand	2200 kWh/a	Based on IEA Task 44[9]
Collector	32 m^2 selective flat plate collector/tilted 45°, south	Type 832[10]
Storage tank		
Volume	1000 l / 3000 l	Type 340 [11]
Heat loss rate	Insulation 0.1 m with 0.037 W/mK, overall heat loss 4.1 W/k	
Heat pump		
Working point B0/W35 (DIN EN 255)	Heating power 8.1 kW (condenser output), COP 4.8	Type 401[12] and Type 292 for flow rate adaption [13]
Volume flow rates	Evaporator 1.9 m^3/h, condenser 0.7 m^3/h	
Dynamics	Heat up constant 30 s, cool down constant 5 min, minimum turn-off time 10 min	
Electrical Heater	Power 7 kW	
Heat source	Borehole with 70 m depth	Type 557 [14]

The main evaluation value is the overall energy consumption of the system including pumps and controllers, which in case of heat pump systems is solely an electricity consumption. In addition to the burners' gas consumption, the energy demand in the boiler system includes also the electricity consumed by the circulation pumps. For comparable results all electricity values are multiplied with a factor of 2.5.

The solar fraction defined in Eq. (1) is determined by the solar input, which considers the whole solar heat to storage and space heating circuit as valuable.

$$f_{Sol} = \frac{Q_C}{Q_C + Q_{HP}} = \frac{Q_{C,Storage} + Q_{C,Direct}}{Q_{C,Storage} + Q_{C,Direct} + Q_{HP}} \qquad (1)$$

This definition leads to higher fsol- values if compared to definitions based on the demand of the building at constant inner temperature.

4. Results

4.1. Systems equipped with heat pump

Fig. 2 shows the solar fraction and the energy consumption of all seven systems depending on the collector area. In the diagram, the storage volume is fixed at 3000 l for the buffer systems and 1000 l for the direct and the Rad + TA systems. The direct heating mode is used until a room temperature of 24 °C, see Section 4.3.

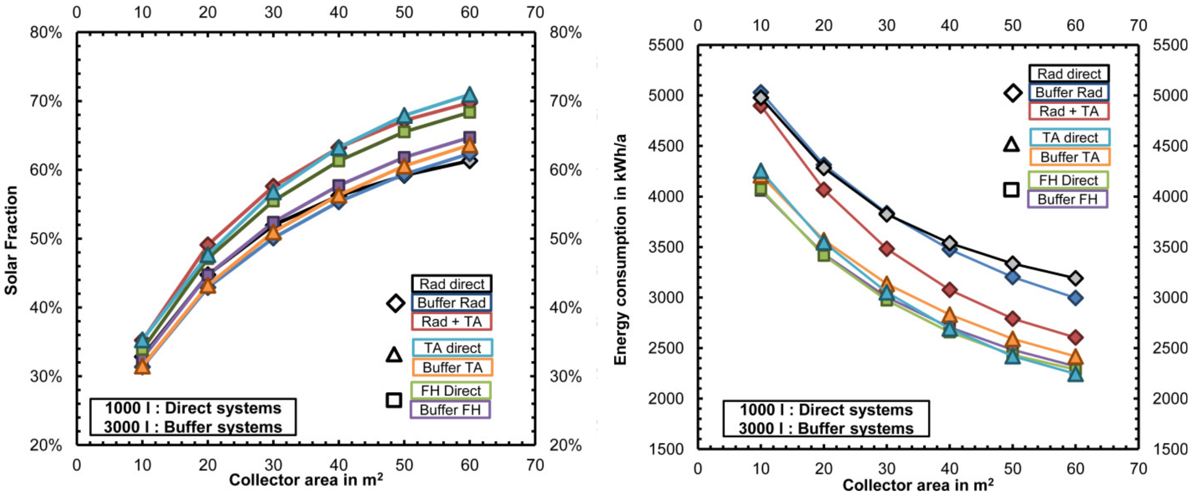

Fig. 2: Solar fraction (left) and energy consumption (b) of the systems with different collector areas and one storage volume, energy consumption of the reference buffer system without any solar collectors and a smaller storage tank of 300 l: 6550 kWh (Rad), 5700 kWh/a (FH), 5920 kWh/a (TA)

The diagram in Fig. 2 allows a comparison of the system concepts:

- The solar fraction is higher in the systems with a direct integration of solar heat although the tank volume is three times larger in the buffer systems. An exception is the system with radiators with a low solar input in the direct mode due to the higher operating temperature. The heating element and its temperature level have a large impact on the solar heat input in the direct mode which is far less pronounced in the buffer systems.
- The solar input in the direct systems is used to increase the room temperature above the set value of 20 °C. Exemplarily in the case of floor heating, the average temperature in the heated zones during the heating period October to April is 20.5 °C to 20.6 °C in the buffer system and 20.6 °C to 21.8 °C in the direct system for collector areas of 10 to 60 m². Since the higher room temperatures also increase the heat losses of the building, the additional solar heat only partly lowers the energy consumption. At a collector area of 10 m² there is only a small improvement with the direct charging mode but already at collector areas above 20 m² the direct systems perform considerably better.
- If floor heating is used, the energy consumption of buffer and direct system is almost identical. Based on a buffer system with 1000 l, the energy consumption may be reduced in the same magnitude by a three times larger buffer storage or by integrating the direct heating mode. With TA the direct system results even in a lower energy consumption than the buffer system especially at larger collector areas.
- With radiators the direct mode leads to a higher energy consumption than the buffer system while the system Rad + TA shows a better system performance than both radiator systems. However, the system Rad + TA has considerably higher energy consumptions than the other systems with FH or TA.

4.2. Systems equipped with gas boiler

The type of auxiliary heater affects the energy consumption and thus has a significant impact on the system performance. According to the method explained in Section 2, the simulation results are used to estimate the performance within the concepts if equipped with a condensing gas boiler. Compared to heat pumps, the performance of such a boiler is less dependent on the storage temperature level. Fig. 3 shows the solar fraction and the energy consumption for the same system configurations as in Fig. 2. Since the calculation method only affects the auxiliary energy consumption, the values for the solar fraction are identical.

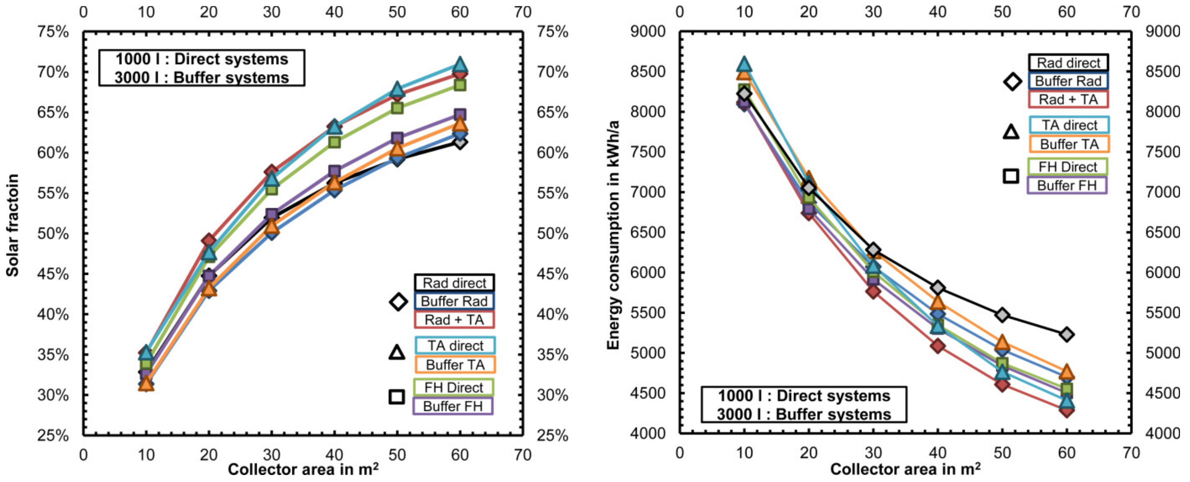

Fig. 3: Solar fraction (left) and energy consumption (right) of the systems with different collector areas and one storage volume for the systems equipped with a boiler, energy consumption of the reference buffer system without any solar collectors and a smaller storage tank of 300 l: 11060 kWh (Rad), 11320 kWh/a (FH), 11660 kWh/a (TA)

The diagram shows significant differences compared to the heat pump systems:

- The energy consumption increases since no heat from the ground is used for auxiliary heating. With radiators, the surplus is around 60 % while it reaches 100 % in the case of TA and FH. Due to the behavior of the boiler, the systems' energy consumption is much less influenced by the space heating operation temperature which reduces the differences in energy consumption between the system concepts.
- The space heating type influences the solar yield and the amount of heat necessary for space heating. Since a low space heating temperature does not improve the boiler efficiency significantly, these effects are more dominant. Due to a higher heat demand of the boiler, the performance of the TA buffer system is worse than the radiator buffer system.
- Like in the heat pump systems, the direct radiator system has the lowest solar fraction and the highest energy consumption. In contrast, the Rad + TA system with its lower space heat demand and a high solar yield reveals the lowest energy consumption at collector areas above 10 m².

In conclusion, the boiler is less affected by the space heating temperature level leading to a better performance of the systems equipped with radiators. However, the space heating operating temperature still influences the collector performance, especially in the direct systems. This is seen in the low performance of the direct radiator system at higher collector areas. If radiators are used, the implementation of a solar heated thermal activation (system Rad + TA) leads to a much higher energy reduction which also outperforms an increase of the storage volume to 3000 l (system buffer Rad).

4.3. Increasing the room temperature

Systems with a direct solar heating mode use the building itself as an additional storage for solar heat. In order to avoid an overheating of the rooms, the direct mode is only active if the room temperature is below a preset maximum comfort temperature, basically set to 24 °C. With a higher temperature limit, the solar heat stored within the building may be increased while a lower temperature would reduce the direct solar input. These effects are analyzed by varying the maximum room set temperature between 20 °C and 27 °C; 20 °C represents the room set temperature for the usual heating mode via the buffer storage. Fig. 4 shows the results exemplarily for the FH direct system and the system Rad + TA, each equipped with a collector area of 30 m² and a buffer storage of 1000 l.

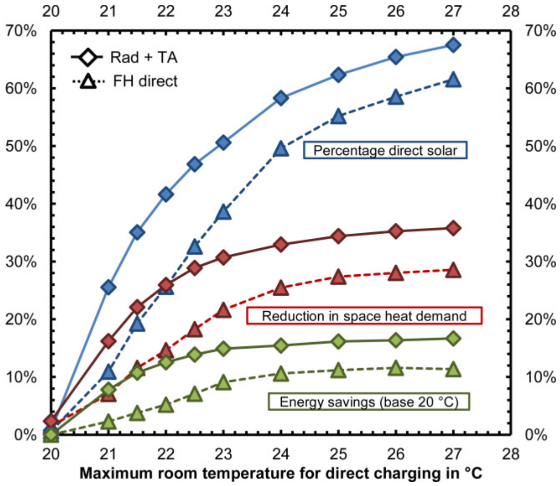

Fig. 4: Variation in the maximum room temperature for the direct solar charging mode for the systems FH direct and Rad + TA: Share of the direct solar heating compared to the overall collector yield, reduction in space heat demand via buffer storage compared to the system without direct solar heating and energy savings compared to the variant with a limit of 20 °C

The diagram shows an increasing share of direct solar heating if a higher room temperature limit is used. In maximum, the direct solar yield reaches more than 60 % in case of the system FH direct and almost 70 % in case of the system Rad + TA. The latter has a higher direct solar input since the solar thermal activation is operated independently from the radiators which is not possible in the direct systems.

Although the direct solar input also increases at temperature limits above 24 °C, the change in the space heat demand is small. Likewise, the energy savings only increase up to a temperature limit of 24 °C, above that value the energy consumption almost stagnates. Therefore, a set value of 24 °C is a sufficient upper value for storing the maximum of useful solar heat within the building. In addition to that, the hours of uncomfortably high room temperatures above 27 °C increase at temperature limits above 24 °C while remaining unchanged at limits of 24 °C or below.

5. Conclusions of the system simulations

The investigation compares the simulated energetic performance of direct solar heating systems with standard concepts of solar combisystems. The direct integration is able to increase the solar fraction significantly, if an element with low operation temperatures is used for space heating. In combination with radiators and high operation temperatures, the direct charging is not recommended. Compared to a buffer system, the direct mode increases the solar yield only at smaller buffer storage volumes. In case of a larger buffer storage, the direct mode is competing with the storage charging. In such a system the solar yield increases only slightly and the solar heat is distributed to both heat sinks. Thus, the maximum reachable solar fraction at a given collector area can only slightly be increased by the direct integration. However, a high solar fraction can be reached with a smaller storage volume.

Fig. 2 shows that a solar fraction of 50 % based on a buffer FH system with 30 m² and 1000 l can either be reached by a larger storage tank of 3000 l or the implementation of the direct mode. Compared to that, a system including both measures – a larger storage tank and the direct charging mode – does not lead to a considerable improvement and is not recommended. The direct solar space heating uses the building as storage.

Instead of the heat pump, a condensing gas boiler may be used as auxiliary heater. Due to the less pronounced efficiency dependence on the inlet temperature the space heating type and its operation temperature have a lower impact on the system performance. With such an auxiliary heater the system Rad + TA performs best, since the solar heat can be used independently of the conventional heating system.

Apart from the energy consumption, the concepts may also be evaluated concerning factors like system costs, complexity and comfort. During summer, the solar thermal system may affect the comfort by inducing higher room temperatures. The direct solar charging of the heat distribution element primarily takes place in the heating period (characterized by the 24 h average ambient temperature being below 15 °C) and higher temperatures are avoided due to a maximum room temperature for direct charging (see Section 4.3). On the contrary, the heat losses of the solar buffer storage occur in the whole year and reach the highest amount in summer when the storage tank is often charged to its maximum set value.

The system complexity is an indicator for the installation effort and error-rate and also affects the frequency of failures during operation. The complexity is defined by the hydraulics and the control. The hydraulic connections in the buffer system are simple and mature requiring one heat exchanger in the solar loop. The additional effort in the direct system compared to the buffer system is comparably low requiring one diverter after the heat exchanger, a switching valve in front of the space heating circuit and a third solar circulation pump. In contrast, the direct systems require a control which not only operates the collector pump but also has to decide how the solar heat is used optimally – for storage charging or for direct space heating. Therefore, the control is more complex and features a lot of parameters which may be a source of errors. While the control in the Rad + TA system is similar to the direct systems, the system layout is more complex due to the two separate heating systems used.

The complexity also gives hints regarding the system costs. Within the buffer systems, the storage itself is the crucial component for the cost calculation. The storage has to be large in order to reach a high solar yield. For high solar fractions around 50 % and more, the storage volume has to be 3000 l at minimum. Such a storage is expensive and not easy to integrate into the building. The storage can be smaller in the direct systems reducing the costs for this component, especially if a high solar fraction is favored. The costs for the additional components are low, only the complex control and its sensors may be less cost-efficient. The storage volume may also be reduced in the Rad + TA system. However, the two parallel heating elements lead to significantly higher costs compared to the direct systems.

6. Prototype

A prototype building was built in order to gain practical experiences with the direct integration of solar heat in the space heating circuit. The concept realized corresponds to the Rad + TA system according to Fig. 1. Within an experimental stage, the main adjustments of the solar heated thermal activation and its control are analyzed in detail. Since the building is inhabited, effects on the room comfort have to be excluded. Here, the Rad + TA system has the advantage that both heating systems are charged independently, ensuring that the room temperature always reaches the value set by the inhabitants.

The solar thermal system of the prototype building has the aim to contribute at least 50 % to the overall heat demand. For such a so-called solar active house, the Rad + TA system represents a cost-efficient alternative to the usual concepts with a large storage tank with volumes of 5-10 m³ in single family houses [2]. In order to reach the high solar yield, the building has a flat plate collector with an area slightly above 30 m² but, according to the system concept, only a buffer storage volume of 1000 l. The building itself has three stories (heated area 270 m²) and a comparatively high insulation standard with a specific space heat demand of 45 kWh/m²a (according to pre-calculations during the planning process). The ceiling between cellar and ground floor as well as the ceiling between ground and first floor are activated via pipes embedded in the concrete. A heat pump is used as the auxiliary heater, receiving its heat from a horizontal ground heat exchanger. In contrast to the system layout described in Section 2, the collector is in addition used for charging the ground heat exchanger. This intermittent regeneration allows small GHE dimensions and reduces the collector stagnation hours. The control in the building is a further development of the variant presented in Section 2.4 including the regeneration mode.

The prototype was completed in spring 2015 in Hanover, Germany. Fig. 5 shows the building during construction and after the completion.

Fig. 5: Prototype building. Upper left: Implementation of solar thermal collectors, Upper right: Construction of thermal activation layer between cellar and ground floor, Lower left: Heating room after completion with data recording unit in the center, Lower right: Building after completion

Within the prototype, the system concept Rad + TA has been installed successfully, the first measurements between April and November prove that the system operates as desired and that the direct mode leads to a high solar yield especially in the autumn months. The measurement period will continue for the next 15 months to gain more results especially including the winter performance.

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