SOLAR ROOF TILES - POTENTIALS FOR ENERGY-EFFICIENT BUILDINGS IN HISTORIC BUILDING STOCK

SOLARDACHSTEINE - POTENZIALE FÜR ENERGIE-EFFIZIENTE GEBÄUDE IM HISTORISCHEN BAUBESTAND

Harald Garrecht[1,2], David Oexle[1], Luka Lacković[1], Lena Teichmann[1]

[1] *Institute of Construction Materials, University of Stuttgart*

[2] *Materials Testing Institute (MPA), University of Stuttgart, Otto-Graf-Institute*

SUMMARY

As part of a BMWI joint research project [1], the Institute of Construction Materials (IWB) at the University of Stuttgart together with the Margarethe Krupp Foundation for Housing Welfare (MKS) in Essen and the research partner at RWTH Aachen University, the Chair of Integrated Analog Circuits (IAS) in close cooperation with the company partners Eckpack and Noventec, a hybrid solar roof tile made of a high-performance fine-grain concrete was developed, prototypically manufactured and tested in the laboratory, which, after sampling by the owner of the listed buildings of the historic garden city Margarethenhöhe in Essen (Fig. 1) and the associated monument authorities, the roofs of five historic buildings in the district were approved for covering with this new type of solar hybrid roof tile mad out of a colored fine grain concrete (SHRT).

ZUSAMMENFASSUNG

Im Rahmen eines BMWI-Verbundforschungsvorhaben [1] wurde seitens des Instituts Werkstoffe im Bauwesen (IWB) der Universität Stuttgart gemeinsam mit der Margarethe Krupp Stiftung für Wohnungsfürsorge (MKS) in Essen sowie dem Forschungspartner der RWTH Aachen, dem Lehrstuhl für Integrierte Analogschaltungen (IAS) in enger Zusammenarbeit mit den Unternehmenspartnern Eckpack und Noventec ein hybrider Solardachstein aus einem durchgefärbten Hochleistungsfeinkornbeton entwickelt, prototypisch hergestellt und im Labor erprobt, der nach einer Bemusterung durch die Eigentümerin der denkmalgeschützten Gebäude der historischen Gartenstadt Margarethenhöhe in Essen (Fig. 1) und die

zugeordneten Denkmalbehörden freigegeben wurde, um die Dächer von fünf historischen Quartiersgebäuden mit diesem neuartigen solarhybriden Dachstein (SHDS) einzudecken.

Fig. 1: Development “Small Market"
(Source: Christiane Ditzen, University of Stuttgart)

1. PRESENTATION OF THE JOINT PROJECT

In the joint project "Energy-efficient housing estates through sustainable concepts for listed buildings - Energy-optimized Margarethenhöhe Essen Quarter (EnQM)" [1], it is to be shown how the energy efficiency of a listed quarter [2] can be significantly increased by means of energy-efficient refurbishment in conjunction with innovative building technology and intelligent electrical, thermal and digital networking of all buildings with one another, and how a virtually climate-neutral supply can be achieved (see Fig. 2). In addition to photovoltaics integrated into the roof tiles and solar thermal energy, the innovative components used in the project are geothermal probes for geothermal heat recovery [3, 4]. The borehole heat exchangers also serve to store thermal energy, as the solar heat gained from the SHRT are also used to regenerate the ground during non-heating periods. However, the solar heat gained of the SHRT is also used for domestic hot water heating.

In order to be able to use the geothermal heat and the heat gained by the SHRT also in the transitional phases in the best possible way by means of heat pumps for the heat supply of the buildings, it is desirable to realize the heat transfer at the lowest possible temperature level (LowEX). In this case, the use of floor heating systems is recommended, which can provide the required room heat with a flow temperature of about 35°C to 45°C if the floor heating systems are sufficiently installed. At such transfer temperatures, highly efficient heat pumps with particularly high coefficients of performance (COP > 5.0) can be operated. System approaches at such low temperature levels work with so-called LowEx components. These include the heat pump, systems for heat recovery from renewable energies such as geothermal and solar heat, wall and/or floor heating systems, low-temperature storage tanks, cold local heating networks, etc. However, in order to be able to realize a climate-neutral heat supply in listed districts with such approaches, measures suitable for listed buildings are required to limit heat losses via the building envelope surfaces and compatible concepts for the integration of floor and/or wall heating systems for heat transfer. In the project, floor heating systems are used in the demonstration buildings that have a low system height of less than 50 mm and can therefore often be integrated into the historic buildings in a way that is compatible with the preservation of historic monuments. In areas where the monument preservation authorities cannot agree to a change in the floor or wall situation, alternative concepts must be developed and implemented.

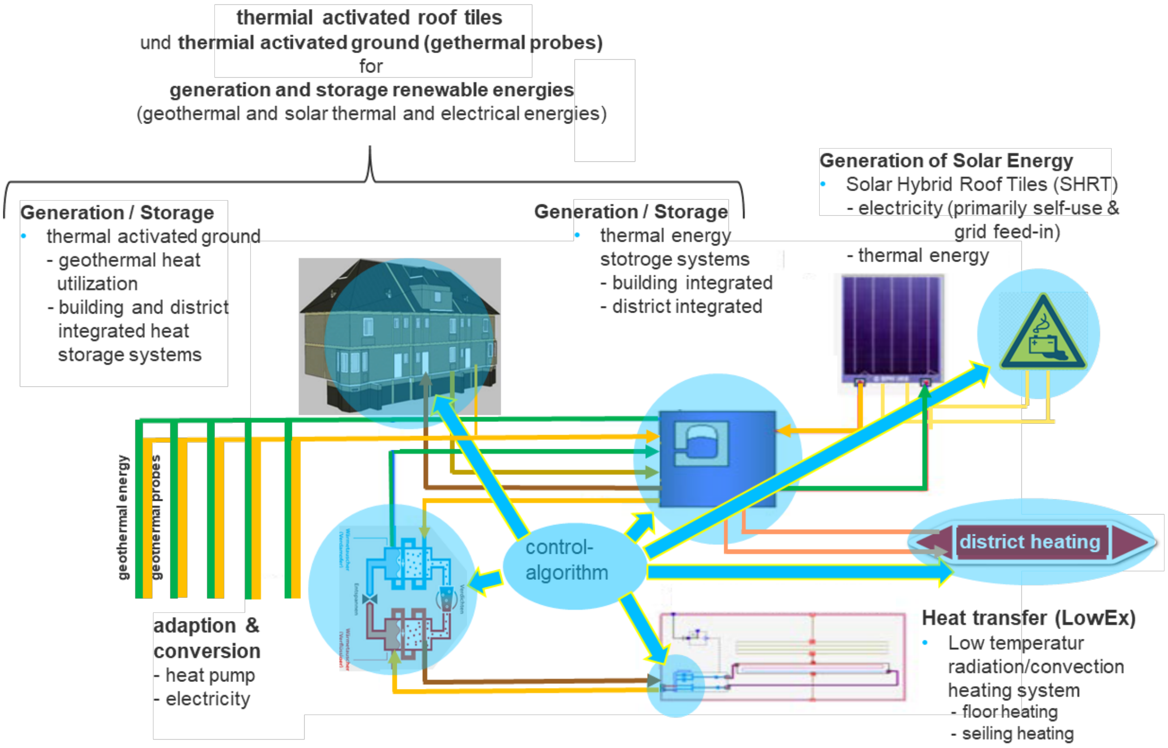


Fig. 2: Key energy supply technologies: generating, storing, using and sharing locally available renewable energy

To increase the thermal resistance of the exterior walls, three-centimeter-thick high-efficiency aerogel thermal insulation plasters were used with the company's partner Cerabran to reduce transmission heat losses. Usually, the roof covering is renewed in the course of a building renovation and, in this context, a thermal improvement of the roof construction is also carried out in coordination with the preservation of historic monuments. As far as possible, the floors of the ground floor areas with basements also receive a thermal improvement. With the help of these measures, it will be possible to operate the room areas of the listed buildings at a LowEx temperature level even during cold weather periods. Accordingly, the heat pump can achieve a high coefficient of performance at a flow temperature of the floor heating system of 35°C to 45°C. Thanks to the regeneration of the ground in summer with the solar heat recovered via the SHRT, the heat pump can even be operated with a consistently high coefficient of performance of over 5.0 at a flow temperature of 35°C.

Fortunately, the electrical activation of the SHRT by means of the roof tile-integrated solar modules allows large amounts of electrical energy to be generated. Even under conservative considerations, an expected solar electricity yield of 100 $\mathrm{kWh_{el}/(m^2a)}$ with the roof areas to be occupied of the five demonstration buildings is sufficient to cover the electricity demand of the building-integrated heat pump, at least in an annual balance sheet. Since the heat pump has to provide the heat required for heating during the cold and less sunny months, it is unavoidable to draw electricity from the existing power grid. The only remedy would be large electrical storage units of several hundred to one thousand kilowatt hours, but these are currently not economically feasible. Smaller electrical storage units are indispensable in the system approach, however, in order to be able to feed the energy generated via the SHRT into the existing supply grid on sunny days, at least in a way that serves the grid. For this purpose, building- and neighborhood-integrated electrical storage units are used in the project. Similarly, building-integrated thermal energy storage systems based on phase change material (PCM) will be considered in the heat supply concept in order to be able to incorporate surpluses from the external power grid to relieve the load on the grid during the heating period and to bring the heat in the ground and in the SHRT up to the supply temperature level. PCM storage systems are excellently suited for storing heat at a low temperature level with low losses.

All in all, a nearly climate-neutral heat supply concept can be realized in the listed buildings. Assuming realistic boundary conditions, the analyses carried out so far using dynamic building simulation have produced more than promising results. The measures and concepts are to be implemented in the five demonstration buildings by the end of 2021, so that with the energy analysis of the monitoring data collected in a comprehensive manner, a meaningful evaluation of the buildings will already be possible after the 2022/23 heating period. The following years will reveal whether the systemic supply approach meets the high expectations of the project.

As can be seen from the section, the SHRT are of central importance in the systemic building approach. It has already been possible to develop a manufacturing concept that is almost suitable for (pre-)series production and to test it in the individual process steps. At least the first 3,000 SHRT of the total of 13,000 SHRT to be manufactured up to March 2022 will have been produced and installed on the roofs.

2. SOLAR HYBRID ROOF TILE (SHRT)

In addition to the usual roof tile functions, the novel solar hybrid roof tile, which is made of a high-performance fine-grain concrete, offers the possibility of recovering solar electric and solar thermal energy accruing on the roof surfaces. Through the solar thermal energy, however, the SHRT can also absorb the environmental heat that is available on days when the sun is low, so that this can be integrated with the help of the heat pump during the transition months to cover the heat demand. Even if these gains can be theoretically demonstrated with the aid of thermal building simulation, only measurements under real environmental conditions in the five demonstration buildings will allow reliable statements to be made about the contribution that the environmental heat can make to heat coverage on sunless days.

The major challenge from the development to the current preparation of the (pre-) series production of the roof tile is to match the geometry and appearance of the SHRT to the roof tiles normally used in the Margarethenhöhe so that both the MKS and the monument preservation authorities can agree to the installation of the replicated roof tiles, but now extended by additional functions, on the roof surfaces of the listed buildings in the garden city. The biggest problem had to be solved for the company partner responsible for the PV side, Eckpack. The standard roof tile shown in Fig. 3 has a wave shape (S-wave). As is well known, flat monocrystalline solar cells are used in PV laminates, which are made of wavers and are to be interconnected to form strings for the production of the PV module. Several parallel strings are brought together on a laminate, which have to be formed into the S-wave shape. Enormous development work had to be carried out by the company partner with its partner field in order to be able to provide an almost S-shaped laminate. The shaping of the PV modules from a flat to a corrugated shape proved to be problematic. For this purpose, the laminates are bent into the desired corrugated shape using a specifically designed forming unit. However, the bending process applies high bending stresses to the solar cells, which break as brittle silicon wafers when the tensile strength is exceeded and thus fail. Thanks to innovative interconnection techniques, the company's partner has succeeded in ensuring that even if individual solar cells fail, there are no severe power losses due to cell breakage. The performance of the corrugated SHRT is measured by the research partner IAS. Here, initial test series on a cluster of SHRT showed that, compared to flat modules, the electrical solar yield of the corrugated SHRT drops less than originally expected. In fact, the S-wave offers advantages with respect to the yield of diffuse radiation.

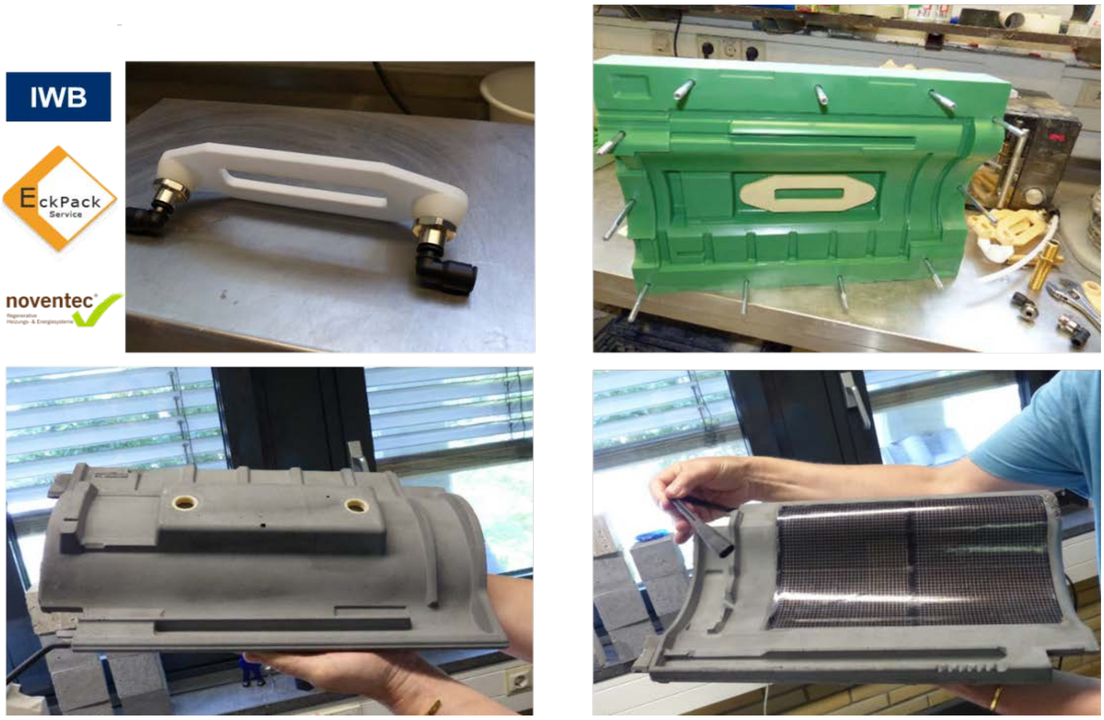


Fig. 3: Solar hybrid roof tile - development steps and subcomponents heat exchanger, PV laminate (here CIGS) and 3D formwork

In addition to electrical activation, a concept for thermal activation of the SHRT was developed, prototyped and tested together with the company's partner Noventec, so that in combination with solar-electrical activation, a multifunctional roof tile was developed that corresponds in its geometry to the roof tiles to be laid on Margarethenhöhe in Essen. In order to reproduce the visual appearance of the roof tile, a color-matched coating was first applied to the fine-grain concrete surface. In further development steps, however, a fine-grain concrete colored through with suitable pigment mixtures was realized.

After the first prototypes had been produced and tested in terms of their visual appearance and thermal as well as electrical effect, a sampling of the SHRT was agreed with the MKS and the preservation of monuments in the fall of 2019. Fig. 4 shows a demonstration setup for the mixed installation of the SHRT developed in the joint project with the original roof tiles. In addition, four roof tiles of an existing roof were replaced by two new roof tiles and two solar hybrid roof tiles made of fine-grain concrete and their visual appearance was sampled. The result (Fig. 5) convinced the MKS as well as the monument preservation authorities, so that approval was given to cover the roofs of five demonstration buildings, on which the holistic energy concept for the realization of almost climate-neutral buildings can thus be tested.

Fig. 4: Sampling of SHRT on Margarethenhöhe by MKS and Historic Preservation (Roof tiles without PV laminate are original roof tiles)

If the theoretically elaborated energy improvement potentials of the measures prove to be applicable to lead the buildings in the historic stock towards climate neutrality by means of components and concepts that are appropriate to thinking, the foundation will successively refurbish its stock of 800 buildings on the Margarethenhöhe in an appropriate manner by 2045, taking into account the aspects of economic efficiency of the measures, in order to be able to ensure climate neutrality in the quarter with the selected approaches and an intelligent energy flow management.

3. FEATURES OF THE DEVELOPED SHRT

An important component of the heat supply concept for the holistic overall approach is the solar hybrid roof tile, which can be used to generate the thermal and electrical solar energy produced on the roof surfaces. The solar electricity can be used directly for the building's own use or fed into an electrical storage system. Depending on the temperature level, the heat generated on the roof can either be used directly during the heating period or can be raised particularly efficiently to the flow temperature of the heating system using the heat pump. Heat that cannot be used can be fed to the geothermal probes for regeneration, especially during sunny, non-heating weather periods, in order to maximize the performance of the geothermal reservoir. Consequently, the electrical and thermal energy gains of the solar hybrid roof tiles are of central importance in the project.

Fig. 5: View of the existing roof after replacement of the roof tiles by SHRT during sampling

3.1 Material selection and compound composition

Roof tiles are formed from clay with an earth-moist consistency using high pressures and fired in a tunnel kiln to sintering temperatures to produce a ceramic with high strength and impermeability. The production process with its very high temperatures prevents heat exchangers or PV modules from being integrated into the blank.

At IWB, therefore, a concept was developed with the company partners Eckpack and Noventec, based on a high-performance fine-grain concrete with an easily flowable and self-compacting consistency, which can be filled into a mold in which the two inlays in the form of the heat exchanger and the PV laminate are geometrically positioned and fixed beforehand. The mold is a complex 3D formwork that has to be filled by the flowable concrete without voids or pores. In the process, the heat exchanger must be completely enclosed. The PV laminate to be fixed to the topside formwork must also be permanently coupled to the concrete with a high adhesive bond.

First of all, comprehensive formulation development was required in order to be able to produce a fine-grain concrete with a suitable mix composition that can withstand the weather-related and mechanical effects in the hardened state in the long term.

In a further step, the fine-grained mixture had to be adapted in its color appearance to the roof tiles used in the Margarethenhöhe. Numerous mixing tests were carried out in order to work out a suitable fine-grained concrete mixture of various Portland (CEM I) and Portland composite cements (CEM II) as well as other reactive and inert concrete admixtures (limestone flours, fly ash, oil shale slag, etc.) with a wide variety of color pigments, which, together with suitable concrete admixtures, achieves the high requirements for both fresh and hardened concrete properties (see sample in Fig. 6).

Fig. 6: Material developments for finding the suitable compound composition, color shade and for integrating the PV laminates - test series

The aim was to be able to work out a through-colored fine-grain concrete formulation which, in the hardened state, corresponds to the brown-gray color appearance of the original brick. Fig. 6 shows different surface qualities of a small selection of the investigated mixtures with and without PV laminate on top.

3.2 Geometric and optical adjustment of the PV modules

The replication of a corrugated roof tile shape required that the flat and level design of the PV laminates usually used by module manufacturers be converted into a corrugated roof shape. Fig. 7 shows the parallel strings, which electrically connect the solar cells using a circuit specifically developed by the company partners. In a first series, monocrystalline cells were combined into strings by the company partners. The PV laminate originally had a total of 9 parallel strings. However, it became apparent that due to the strongly corrugated shape of the roof tile, the solar cells had to be strongly bent. Bending the PV laminates without cell breakage is hardly possible due to the brittle material behavior of the PV cells. After a long series of tests to adapt the bending process of the monocrystalline PV laminates, it was first decided to use thin-film modules (CIGS) instead of the parallel strings of monocrystalline cells.

As shown in Figs. 4, 5 and 6 the optically desired result can be achieved comparatively easily with CIGS [5]. However, tests and developments carried out so far have shown that the electrical performance of CIGS modules with the cells currently available on the global market is not sufficient. Whereas monocrystalline PV cells could achieve 7 W of power in direct sunlight through the parallel strings with a roof tile, the CIGS modules achieved only 2 to 4 W. Consequently, new process engineering steps were necessary to be able to fix the neighboring strings to the formwork of the roof tile as far as possible without cell breakage despite the corrugated shape. In the early summer of 2021, it was finally possible to analyze the steps required in terms of process technology in detail with the company partners in order to work out a solution for a shape adaptation of the PV laminates suitable for series production in pre-production test series.

3.3 Thermal activation by means of integrated heat exchangers

In a first step, the integration of copper tubes to take over the heat exchanger function was analyzed numerically. Various copper tube components were tested, with the copper tubes being arranged in the lower to middle third of the solar roof tile as far as possible. In order to maximize the contact area and thus the heat transfer due to thermal conduction between the copper tube and the roof tile body, bent copper tubes were initially provided (Fig. 7).

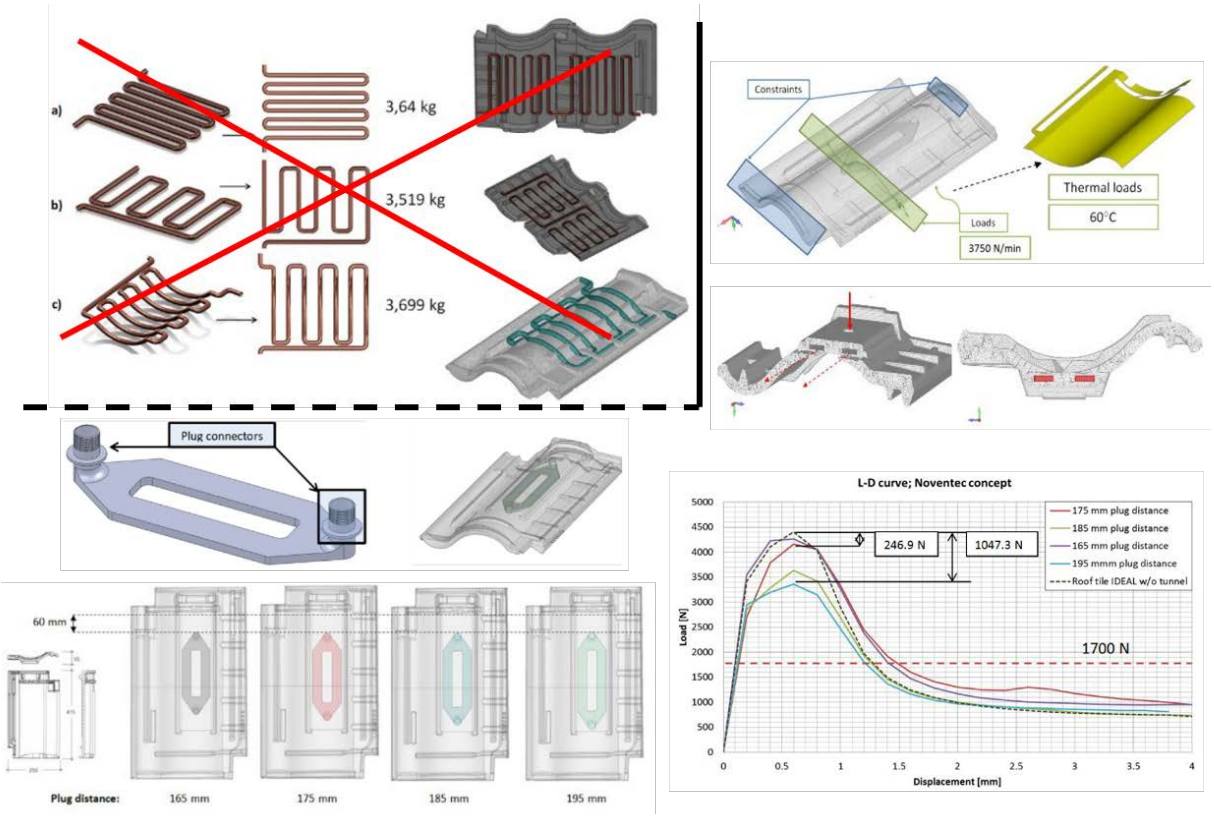


Fig. 7: Design development and fluidic and mechanical optimization of the heat exchanger using CFD and FE simulations

In addition, cost-technical analyses were carried out for the integration of curved copper tube heat exchangers. Not only the favorable efficiency was discussed, but also the high costs.

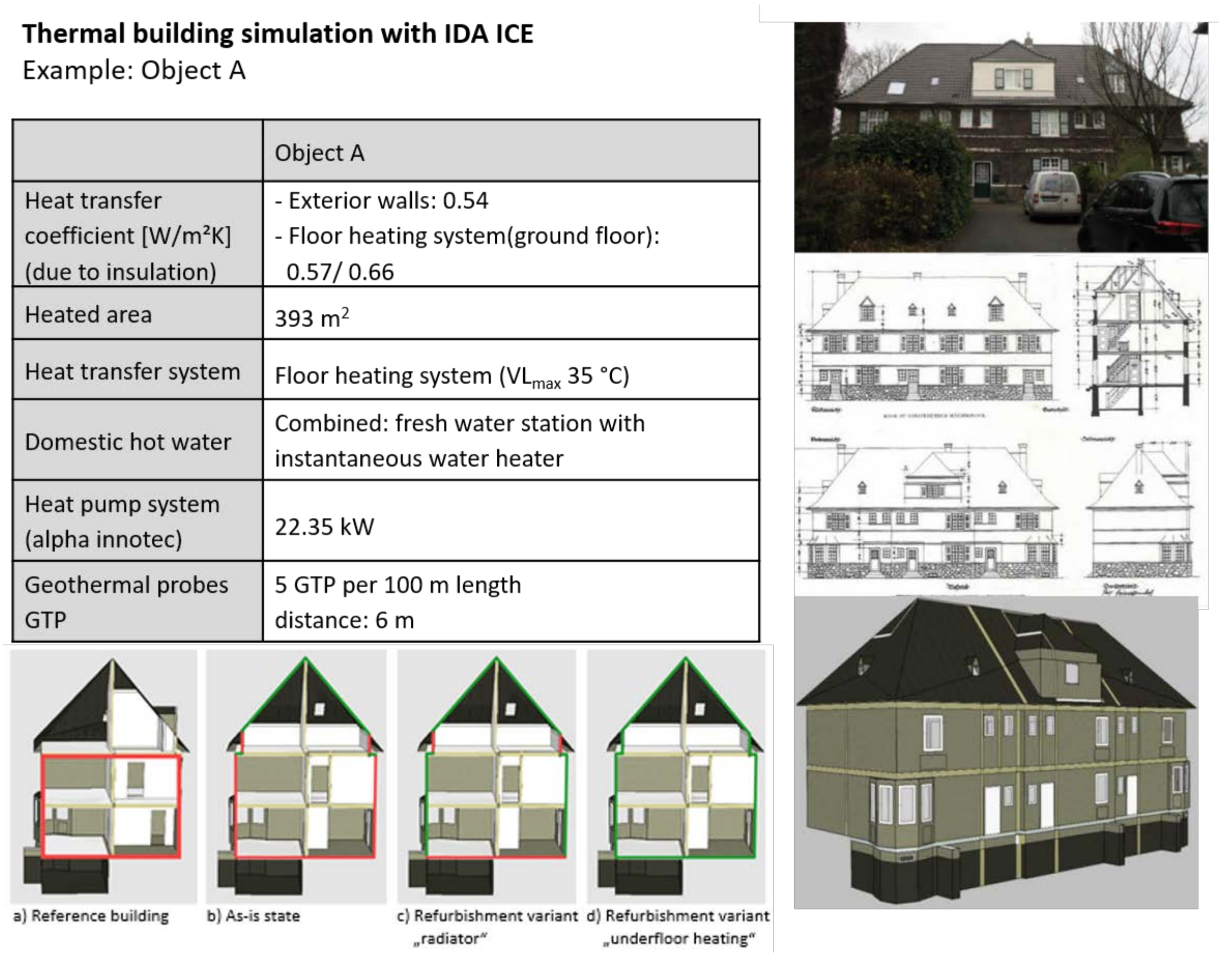
As an alternative to the copper tube heat exchanger, a polymer-based twin-channel component was developped is integrated into the fine-grained concrete for heat transfer. Although the shape of the heat exchanger requires the integration of the twin-channel heat exchanger, its efficiency and thermal performance to be maximized. Despite the integration of the heat exchanger and the resulting high structural stability, the behavior of the fine-grained concretes had to be investigated in depth and optimized. With the help of 3D flow simulations, it was possible to work out the ideal geometry of the twin-channel heat exchangers and also the heat transfer behavior of the individual roof tile, and to analyze the effect of the thermally activated roof tiles connected in series by means of simulation. The fluid temperature at the outlet of a roof tile can be taken as the inlet temperature of the next tile.

After the simulations with the twin-channel heat exchanger were successful both under static and thermal aspects, the first prototype heat exchangers were manufactured as 3D models from plastic using a 3D printer. In order to significantly reduce unit costs, the heat exchangers were injection molded on the basis of the findings from the test series.

For the 3D model of the solar hybrid concrete roof tile, a top and bottom formwork was produced in which the integration of the heat exchanger as well as the corrugated PV laminates was taken into account. With this formwork, which was duplicated after initial checks, the proto-typical SHRT developments could be made, in which new prototypes could be produced after each adjustment of the mixture composition, the laminate production and the modification of the heat exchanger, in order to experimentally test their optical and technical suitability and performance. In the meantime, a further developed battery formwork concept has been developed from the 3D formwork designed for single block production, which can be made available at the end of July 2021, so that from August onwards, 3,000 SHRT are to be produced by mid-September with series production, and from then onwards a further 10,000 SHRT are to be produced by mid-November 2021, in order to be able to cover all the roofs of the five demonstration buildings with the SHRT by mid-December 2021.

4. CLIMATE-NEUTRAL BUILDING CONCEPT

In the following, the modeling and analysis of the thermal building simulation is briefly described. Three main variants ("Reference existing building 1995", "As-is 2018", "Refurbishment") were analyzed (Fig. 8). The "Refurbishment" variant distinguishes between two types of heat transfer to the room. On the one hand, the heat transfer by means of floor heating (FH) "Refurbishment FH" and on the other hand by means of radiators (R) "Refurbishment R". The calculations performed with the building simulation take into account initial control concepts, in which the operation of SHRT was also considered [4, 5]. The solar heat absorbed by the heat transfer fluid in the SHRT connected in series is stored seasonally for regeneration of the ground via the borehole heat exchangers.



Thermal building simulation with IDA ICE
Example: Object A

	Object A
Heat transfer coefficient [W/m²K] (due to insulation)	- Exterior walls: 0.54 - Floor heating system(ground floor): 0.57/ 0.66
Heated area	393 m^2
Heat transfer system	Floor heating system (VL$_{max}$ 35 °C)
Domestic hot water	Combined: fresh water station with instantaneous water heater
Heat pump system (alpha innotec)	22.35 kW
Geothermal probes GTP	5 GTP per 100 m length distance: 6 m

a) Reference building b) As-is state c) Refurbishment variant „radiator" d) Refurbishment variant „underfloor heating"

Fig. 8: Modeling and energy flow analysis using thermal building simulation

The original plans from 1912 were taken into account in the "Reference existing building 1995" variant (see Fig. 9). The changes made in the building currently under investigation between 1995 and 2018 are taken into account in the "As-is 2018" variant. The two renovation variants differ in terms of both structural and technical measures. The exterior wall surfaces were improved in terms of energy efficiency with interior insulation. An extremely heat-insulating aerogel interior insulation plaster is used in the project. In order not to lose any unnecessary room volume, the plaster thickness will not exceed 3 cm.

Areas	Reference 1995	As-is 2018	Refurbishment & radiators	Refurbishment & floor heating
Heated area [m^2]	249	393	393	393
Number of occupants [persons] (VDI 6002-1)	9.3	10.2	10.2	10.2
Max. Flow temperature [°C]	70	70	45	35
Hot water [°C]	60	60	45	45
Lighting + devices [kWh]	6400	8900	8900	8900
Heat generator heating [kWh]	51070	51090	8500	6704
Heat generator Hot water [kWh]	5760	6180	1560	940
Total heat generator [kWh]	56830	57270	10060	8020
Total geothermal energy [kWh]	-	-	33640	30050
Total energy [kWh]	63230	66170	52600	46970

Fig. 9: Simulation studies of the refurbishment variants taking into account energy upgrading and modernization of plant technology with LowEx components

In order to realize a nearly climate-neutral building, it is necessary to modernize the system technology for heat and hot water supply. In the EnQM project, a heat pump is used which, in combination with the use of environmental energies based on geothermal energy as well as solar energy gains by means of the hybrid roof tiles in conjunction with heat transfer at a very low temperature level, as is possible with floor heating systems, can achieve excellent energy efficiency. The design of the geothermal probes was based on the draft of VDI 4640 sheet 2 [6]. The selected borehole heat exchanger field was verified by further simulations. Thus, a seasonally continuously changing decrease of the ground temperature was observed over a longer period of time (50 years). Accordingly, an ideal arrangement of the borehole heat exchangers can be realized.

4.1 Comparative results of the specific building energy demand

Fig. 10 shows the specific final energy demand of the building in the reference state and for the refurbishment. While the specific final energy demand in the "Reference 1995" variant is approx. 254 kWh/m^{2}a, the "As-is 2018" variant results in a demand of only approx. 169 kWh/m^{2}a. This reduction results from the insulation of the roof and the replacement of the windows with more energy-efficient glazing. On the other hand, if we consider the "Refurbishment FH" variant, the specific energy demand is reduced to 119 kWh/m^{2}a. This noticeable reduction is due to the installation of an aerogel interior insulation plaster and the heat transfer at a very low temperature level by means of underfloor heating.

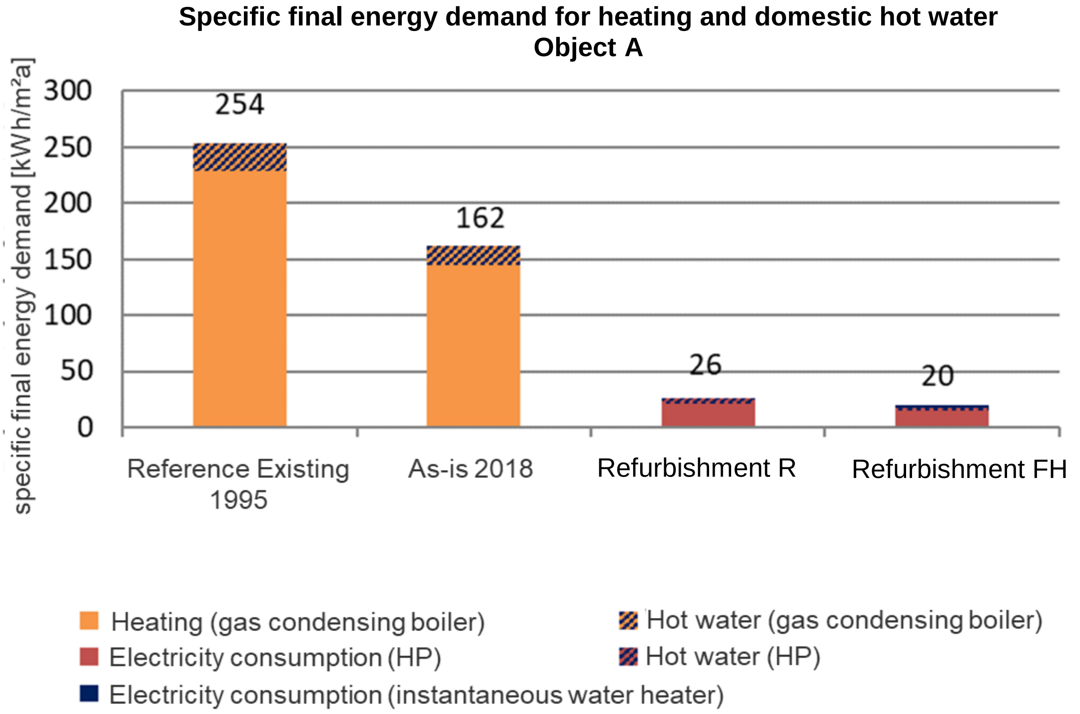


Fig. 10: Comparison of specific final energy requirements for as-is and refurbishment [4]

In the "Refurbishment R" variant, the specific energy demand is slightly higher at 134 kWh/m^{2}a. Even if the energetic improvement of the building envelope is not in the foreground in the listed building stock, the use of innovative system technologies becomes interesting with the reduced heating load. In the present project, a heat pump was selected in conjunction with geothermal probes and the SHRT. Thanks to the reduced final energy demand for heating, most of the energy demand can be covered by the available geothermal energy. By means of the solar heat gains of the SHRT in the non-heating phase, the ground can be regenerated in summer. In this case, the heat pump can be operated at a high coefficient of performance of COP > 5.0 in conjunction with the heat transfer at a low temperature level by means of underfloor heating. In addition, the solar heat obtained via the SHRT during the heating season can also be used to supply heating.

If only the specific energy demand for the heating of the building and for the hot water preparation is considered, minus the coverage by the geothermal energy, a reduction of the specific heat demand from 230 kWh/m^{2}a for the variant "Reference existing building 1995" to 20 kWh/m^{2}a for the variant "Refurbishment FH" is shown. In total, a reduction of approx. 91% is achieved (see diagram in Fig. 10.)

4.2 Dimensioning the heat pump

When dimensioning the heat pump, the heating load of the building is taken as a basis. In addition, surcharges for possible blocking times of the network operator are added in order to determine the required heat pump capacity with this information. The suitable heat pump can be selected on the basis of the calculated power requirement. In the project, a heat pump was selected that can be operated in combination with photovoltaics and solar thermal energy. For the variant with the continued use of the existing radiators, it is also important that the selected heat pump can also provide higher flow temperatures during ongoing heating operation. Thus, the SW 302H3 heat pump was selected for the variant with radiators and the SW 232H3 for the variant with floor heating.

4.3 Design of geothermal probes for the extraction of geothermal energy

Three different sources were considered for the inclusion of geothermal energy: horizontal surface collectors, geothermal baskets and geothermal probes. Depending on the size of the available unsealed land area outside the building, horizontal surface collectors or geothermal baskets can be used. The use of geothermal probes is also limited by the available area. This is especially important if a greater drilling depth would be required. Since the land for all buildings on Margarethenhöhe is owned by the Margarethe Krupp Foundation, there is no need to maintain minimum distances from neighboring properties. If the garden area of a building is not sufficient, the neighboring gardens can theoretically also be used.

In the building simulation, an additional software module was integrated to take the borehole fields into account. This module can be used to simulate several boreholes in any borehole pattern, but they must all have the same length. Among other things, the model calculates the thermal interaction of the boreholes with each other.

4.4 Regeneration

In summer, when no heat is extracted from the soil, natural regeneration of the soil takes place. However, this takes place very slowly. If the heat extraction of the soil during the heating period is very high or if the phase in which no heat extraction takes place is very short, the geothermal heat flux cannot fully compensate for the winter heat extraction. This leads to a cooling of the ground over a longer period of time and, in extreme cases, to a freezing of the borehole heat exchangers [6, 7]. With the regeneration of the ground by the solar heat gains obtained through the SHRT, the ground can be completely regenerated. Accordingly, the ground does not cool down over the years, but the borehole heat exchanger can supply geothermal heat to the heat pump even in the coldest winter periods, at a level that allows the heat pump to generate heat with a high coefficient of performance (COP > 5.0).

Fig. 11 shows over a simulation period of 50 years the provided temperatures of the borehole heat exchangers with regeneration (blue) and without regeneration (brown). The temperatures without regeneration decrease over the years in a typical course. Looking at the temperatures with summer regeneration of the ground by the solar heat gains of the SHRT, it can be seen that the temperature level tends to shift upwards over the simulation period. The annual mean temperature provided increases by about 1 K after 50 years compared to the first year of the simulation [4].

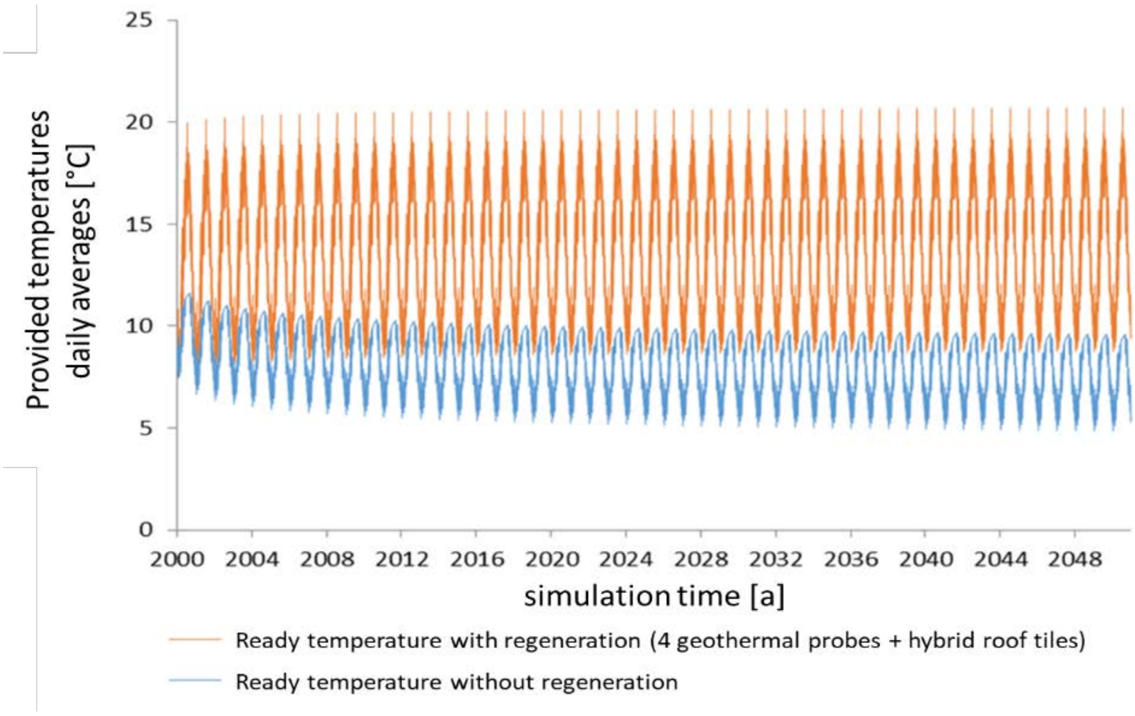


Fig. 11: Temperature provided with and without regeneration for a simulation period of 50 years [4]

5. REMEDIATION CONCEPT AND CONCLUSION

Based on the simulation results, the following renovation concept was favored and recommended for implementation: For heat transfer, underfloor heating is used wherever possible from the point of view of monument preservation. The roof, the floor to the ground and the basement, as well as the exterior walls, will be insulated. The windows will be fitted with double-pane thermal insulation glazing, as agreed between the owner and the monument conservator. Domestic hot water is provided by a fresh hot water station with a combined instantaneous water heater. The underfloor heating is designed in such a way that a maximum flow temperature of 35°C ensures comfort even on cold winter days.

According to the calculations carried out, a number of about five geothermal probes, each with a depth of 100 m, are required per building to cover the heat supply requirements. Fig. 8 shows some information on the design of the plant engineering systems with which the systemic energy supply approach can be realized. Thanks to the use of SHRT, the ground can be regenerated with the solar heat obtained on the roof surfaces [3, 4, 5]. To further increase the efficiency of the overall system, after the implementation of the structural measures in 2022, it can be investigated to what extent the solar heat gained from the SHRT can also be used directly for water heating in summer. In addition, it must be examined to what extent solar heat or environmental heat can also be obtained via the SHRT during the heating period and used efficiently by the heat pump.

Since not only heat but also electricity is harvested with the SHRT, large electrical and thermal energy gains can be achieved throughout the year. In the simulation, the electrical activation of all roof surfaces was taken into account. Thus, the roof surfaces with a northeast and southwest orientation occupy approximately 13 m^2 each. The roof surfaces with an orientation to the southeast and northwest each amount to approx. 83 m^2. The dynamic building simulations show an annual yield of the entire roof area of about 7,750 kWh_{el}/a. This means that the solar electricity yield is sufficient, at least in balance, to operate the heat pump throughout the year with a coefficient of performance of COP > 5.0 using only its own solar electricity.

Another advantage of the coupling of electrical and thermal energy generation by means of the SHRT is the increase in the efficiency of the PV modules. Finally, these are cooled with the regeneration of the ground during the sunny summer months. This leads to a performance increase of the PV modules of > 10% compared to uncooled PV modules.

In summary, the calculation results suggest that a significant increase in energy efficiency towards climate neutrality can also be achieved for listed buildings with the selected systemic approach, without endangering the compatibility of the measures with listed buildings.

The implementation of the measures and concepts developed with theoretical and numerical investigations, which will take place in a few months, will show on the basis of the subsequent analyses and evaluations whether the components developed and prototypically tested in the project will lead in their systemic coupling to climate neutrality of the buildings and the neighborhood.

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