Margarethenhöhe goes towards low-carbon area - sustainable concepts for energy-efficient built heritage

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Abstract. Within the framework of a project funded by the Federal Ministry of Economics and Energy (BMWi) in Germany, it is being examined how, with different approaches, even historic buildings can contribute to an energy-efficient heritage district. Five partners are investigating the legal, structural and technical conditions for improving the building envelope in line with the preservation order, modernizing the buildings and providing a future-oriented energy supply. The inclusion of renewable energies and the digital networking of all components is of particular importance. For this all suitable measures will be adapted in five buildings for demonstration. Then, on basis of an extensive monitoring, the theoretically elaborated model approaches and the results obtained by means of numerical simulations can be validated. The joint project started in 2016. The IWB of University of Stuttgart as coordinator, the Margarethe Krupp Foundation as owner, the Gas and Heat Institute Essen e.V. and two institutes of the RWTH Aachen University, the Institute for Integrated Analog Circuits and the Institute for Building and Climate Technology, are partners in the research network.

Keywords – low-carbon area; energy-efficient built heritage, hybrid roof tiles for energy harvesting, renewable energies, strategies for future-oriented energy-supply

1. Introduction

The project comprises four sub-projects, each with a different focus, in order to work out holistic renovation concepts for the individual buildings as well as prospectively new approaches to energy-efficient energy supply for the entire area, to implement them in the protected district “Margarethenhöhe” and thus to test them at building and district level. The historic area is located in the city of Essen and was planned and built by the architect Georg Metzendorf between 1909 and 1933, donated by Margarethe Krupp [1]. Since 1987, the ensemble of 586 mostly 1.5 to 3.5-story terraced and semi-detached houses has been listed. As one of the first garden cities in Europe, “Margarethenhöhe” is still held in high esteem by its inhabitants and is a popular tourist attraction. The Margarethe Krupp Foundation as the owner strives to preserve the building substance, the high residential value and the unique appearance of the settlement through continuous renovation in close cooperation with the preservation authorities. In order to lead the garden city in the direction of climate neutrality, measures and concepts have been sought and evaluated with which the energy supply of the neighborhood can be realized largely on renewable energies. Therefore, the development of electrically and thermally activated roof tiles and their coupling with soils thermally activated by means of geothermal probes is one of the project's outstanding innovations. Finally, a particularly energy-efficient building concept can be realized in combination with LowEx heat transfer components. With sophisticated thermal building simulations, the aspects of the energetic system considerations are carried out on the building as well as the quarter level. Monitoring to validate the overall approaches derived experimentally, theoretically and on the basis of simulations.
will play a central role, so that the client can transfer the findings gained from five demonstration build-
ingings to the entire neighborhood in the coming decades, with the aim of achieving climate neutrality in
the garden city by 2050.

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

2. Tasks in the project
In the joint project, the existing building stock was first analyzed in detail in exemplary buildings on the
“Margarethenhöhe”. Material samples were taken and the behavior of the building fabric and residents
was recorded by means of component and climate monitoring in order to evaluate the influence of cli-
matic influences. With the help of thermal-hygric component simulations (Software Delphin) and dy-
namic thermal building simulations (IDA-ICE), the listed existing buildings were mapped in digital
building models and the results of these numerical simulations were validated using the data recorded
by measurement. In this way, it was possible to create a reliable basis for the theoretical evaluation of
the planned renovation measures.

All the packages of measures implemented in the project are made up of individual building blocks
which, although already used in practice, are rarely employed in combined system approaches in mon-
uments and are often considered uneconomical. For example, capillary-active, highly heat-insulating
plasters, efficient panel heating systems, modulable heat pumps and electrical and thermal storage units
of various sizes as well as thermostats that regulate according to demand were intensively researched in
the joint project. Heat and electricity come from thermally and electrically activated roof tiles, which
can be laid in monument-compatible formats on suitable sunny roof surfaces in the settlement.

In interdisciplinary research work, simulation studies were used to work out renovation packages for
five apartments and single-family houses in the estate, which are now being implemented in terms of
construction and systems engineering in the course of a tenant changeover. Thanks to intensive coordi-
nation with the responsible persons of the monument authorities throughout the course of the project to
date, novel and innovative technologies can now be tested in the selected structures and apartments and
their effects validated. Without the extensive research and coordination between the partners involved
in the joint project, the use of the technologies would probably not have been approved.

While the researched measures can actually be implemented and thus tested on a small scale in individ-
ual properties, the goals of the research network extend far beyond this: By modelling the entire settle-
ment, different scenarios of energy supply with an increasing share of renewable energy sources can be
compared with the successive energy upgrading of the existing buildings. In this way, the objectives of
the energy turnaround can be transferred to listed districts in the project. After 4 years of research done,
actual all the components and developed methods are implemented on site, to bring the first building in
an energy efficient status towards a climate neutral building. Now in the beginning of 2021 second phase
of the project was started. Beside the transfer of all the outcome of the first phase of the project to four further buildings and strengthening the district aspects of the energy supply, an independent long-term monitoring will be started, in which the effects of the measures on energy consumption and occupant comfort will be documented and analysed.

In the following, the thermal building simulations of an exemplary listed residential building relevant for the holistic neighborhood approach are shown.

3. Concept development of a climate-neutral building in the historical stock

The procedure for the thermal building simulation of the example building is described below. Three main variants ("Reference existing building 1995", "Actual state 2018", "Refurbishment") were analysed to represent the different energy states of the building with the help of simulation tools. The main variant "Refurbishment" is divided into two sub-variants. These differ mainly in the type of heat consumer (underfloor heating and radiators) and are therefore referred for the underfloor heating system to as "Refurbishment FBH" and for the usage of radiators to as "Refurbishment HK". Finally, simulations with initial control concepts for the use of hybrid roof tiles are carried out [4,6]. Hybrid roof tiles are roof tiles that use solar energy for both photovoltaics and solar thermal energy. Photovoltaic cells are applied to the surface, which are used to partially cover the electricity demand. A hollow body, e.g. a plastic element, is integrated inside the roof tile, through which a heat transfer fluid flows. The solar thermal portion can be used, for example, to regenerate the geothermal probes.

The original plans from 1912 were used as the basis for the building structure of the "Reference Existing 1995" variant (Figure 3). The changes to the buildings between 1995 and 2018 were taken into account in the "As-is 2018" variant. The two "Refurbishment" variants differ in both the structural and the systems engineering measures. On the one hand, a variant with the existing radiators was investigated and, on the other hand, a variant with underfloor heating systems. Both variants are based on the assumption that the building envelope surfaces will be upgraded by means of interior insulation. In the project, interior insulation of the exterior wall is based on an aerogel interior plaster. After parameterization, a plaster thickness of 3 cm is assumed. In addition, in the case of the variant with underfloor heating ("renovation FBH"), the floor on the first floor and the sides of the attic are insulated.
In order to achieve the goal of a nearly climate-neutral building stock, a renewal of the system technology is required. In the interdisciplinary work of the project EnQM it was worked out that the use of a heat pump in combination with the use of environmental energies based on geothermal energy in combination with the solar energy gain of the hybrid roof tiles should be realized. The design of the geothermal probes is done according to the VDI 4640 sheet 2 draft [2]. Through further simulations, the selected geothermal probe array was checked and adjusted. For example, the drop in ground temperature over a longer period of time (50 years) was observed and a different arrangement and spacing of the borehole heat exchangers was investigated.

4. Comparison of results of the variants

In the following, the specific energy demand of the different variants is compared, since the living space and thus the annual energy demand of the building changes due to the conversion measures.

Figure 4 shows the specific final energy demand of the building in the reference state as well for the renovation. While the specific final energy demand in the "Reference Existing 1995" variant is approx. 254 kWh/m²a, there is only a demand of approx. 169 kWh/m²a in the "As-is 2018" variant. This reduction in the specific energy demand results from the insulation of the roof and the replacement of the windows with more energy-efficient glazing. If the change of the specific energy demand between the variant "As-is 2018" and the variant "Refurbishment FBH" is considered, a reduction from 169 kWh/m²a to 119 kWh/m²a can be observed. This results from the installation of the aerogel interior insulation plaster as well as the underfloor heating. The reduction in the useful energy demand of the "Refurbishment HK" variant is lower (134 kWh/m²a) than that of the "Refurbishment FBH" variant, since the use of the radiators would make insulation of the first floor too costly and therefore unnecessary. The energy improvement of the building envelope is less decisive in the given design. However, by lowering the heating load, a more innovative system technology can be applied. The use of a heat pump with geothermal energy significantly reduces the final energy demand for heating and hot water, since a large part of the energy demand can be covered by geothermal energy.
If only the specific energy demand for heating the building and for hot water preparation is considered without the share of geothermal energy, a reduction of the specific demand from 230 kWh/m²a of the variant "Reference existing building 1995" to 20 kWh/m²a of the variants "Refurbishment FBH" can be seen. This is a reduction of approx. 91%.

4.1 Design of Heat Pump System

The basis for dimensioning the heat pump is the heating load of the building. In addition, surcharges are added for possible blocking times by the grid power supplier. This results in the required heat pump capacities of the renovation variants in Table 1.

Table 1: Required heat pump capacities of the different variants

| Variant                      | Metzendorfstraße 38 ABC |
|------------------------------|-------------------------|
|                              | \( \dot{Q}_{\text{H,total}} \) [kW] | \( \dot{Q}_{\text{WP, demand}} \) [kW] |
| Renovated with radiators     | 25.4                    | 27.7                     |
| Renovated with underfloor heating | 19.7                    | 21.5                     |

Based on the required performance, the appropriate heat pump is selected. Heat pumps from the SW series manufacturer alpha innotec are selected. These can also be combined with photovoltaics and solar thermal energy and, importantly for the variant with the existing radiators, high flow temperatures are also possible. For the variant with radiators, the type SW 302H3 heat pump is selected, and for the variant with underfloor heating, the SW 232H3. Table 2 shows the technical data of selected heat pumps.

Table 2: Technical data of the selected heat pumps

| Performance data/ Application limits | Renovated with underfloor heating | Renovated with radiators |
|--------------------------------------|----------------------------------|--------------------------|
|                                      | SW 232H3                         | SW 302H3                 |
| Heating power at B0W35               | 22.35                            | 29.6                     |
| COP at B0W35                         | 4.95                             | 4.88                     |
| Heat source return min.,max.         | -5/25                            | -5/25                    |

4.2 Geothermal energy design

Three different sources were considered for the use of geothermal energy: horizontal surface collectors, geothermal baskets, and geothermal probes. According to the design, the choice of the appropriate geothermal component is primarily area-dependent. Depending on how large the available unsealed land area is, horizontal ground collectors or geothermal baskets can be implemented. The implementation of geothermal probes is also limited by the available area, although this is particularly important if the bore-deep becomes problematic. The entire land of the Margarethenhöhe housing estate is owned by the Margarethe-Krupp-Stiftung. As a result, there are no property boundaries for the two buildings and
minimum distances to neighboring properties do not have to be observed. If the area of the garden of the buildings is not sufficient, the neighboring gardens can theoretically also be used. The area required for the various heat extraction means according to the design of VDI 4640 Sheet 2 Draft: 2015 is shown in Table 3. The available area is given in [m²] for the area collectors on the one hand. The complete garden area is taken into account. On the other hand, dimensions of the garden are given in [m]. These refer to a rectangular area in which the geothermal probes can be arranged either linearly or squarely. This is followed in the table by the area required for the horizontal surface collectors and for the geothermal baskets. For the borehole heat exchangers, the requirement for a linear arrangement is given in [m] and for a square arrangement in [m²].

**Table 3**: Area requirement of the withdrawal means and existing unsealed area.

| Areas                           | Metzendorfstraße 38 ABC Radiators & Hot water | Metzendorfstraße 38 ABC Underfloor heat. & Hot water |
|--------------------------------|-----------------------------------------------|-----------------------------------------------------|
| Available unsealed area         | 25 m x 7.8 m or 195 m²                        | 25 m x 7.8 m or 195 m²                              |
| Horizontal collectors           | 861 m²                                        | 501 m²                                              |
| Geothermal baskets              | 790 m²                                        | 440 m²                                              |
| Geothermal probes               | 24 m or 25 m²                                 | 18 m or 25 m²                                       |

An extra module for the simulation of borehole fields can be integrated in IDA ICE. With this model, several boreholes can be simulated in any borehole pattern, but they must all have the same length. Among other things, the model calculates the geothermal temperatures and the interaction between the boreholes. The boreholes can be vertical or inclined. Limitations include the fact that only a homogeneous subsoil, i.e. only one layer as ground structure, can be simulated. In addition, only U-tubes can be used as heat exchangers; coaxial probes are not possible.

4.3 Regeneration

In summer, when no heat is extracted from the ground, a natural regeneration of the ground takes place. However, this occurs very slowly. If the heat extraction during the building heating phase is too high or the phase in which no heat is extracted is too short, the terrestrial heat flux cannot fully compensate for the winter heat extraction. Over a longer period of time, this leads to cooling of the ground and, in extreme cases, to freezing of the ground probes [3].

For this reason, additional simulative consideration was given to how a solar thermal component can be fed into the borehole heat exchangers. The solar energy input is provided by the hybrid roof tiles developed in the joint project. Figure 5 shows the provided temperatures from the borehole heat exchangers with regeneration (blue) and without regeneration (brown) over a simulation period of 50 years. The
temperatures without the regeneration drop over the years in a typical progression. If the temperatures as a result of regeneration are considered, it can be seen that the temperature level shifts minimally upward over the simulation period. The mean annual temperature provided increases by about 1 K after 50 years compared to the first year of simulation [5].

With this variant of regeneration via the hybrid roof tiles, the goal of regeneration to supply as much heat to the soil in summer as was extracted in winter is fulfilled. Cooling over the operating period is prevented by the use of geothermal energy, which means that the system can also be used for longer than the assumed 50 years without a reduction in efficiency. The aim is to heat the ground with the hybrid roof tile in order to regenerate the borehole heat exchangers throughout the year. In order to increase the performance of the heat pump, a concrete water storage tank is additionally inserted between the hybrid roof tile, the geothermal probes and the primary side of the heat pump.

Table 4: Summary input data and energy demand Metzendorfstraße 38 ABC.

| Areas                        | Reference 1995 | As-is 2018 | Renovation radiators | Renovation underfl. heat. |
|------------------------------|----------------|------------|----------------------|--------------------------|
| Heated area                  | 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                    |

5. Refurbishment concept and conclusion
Based on the results of the simulations, the following refurbishment concept is recommended as shown in Table 4. However, this is a purely simulative approach and may differ from object to object.

Table 5: Summary of the plant technology of the implementation recommendations [5]

| Variante         | Objekt A                                      |
|------------------|-----------------------------------------------|
| Heat transfer    | Floor heating system (V_{\text{L max}} 35 °C) |
| Hot water        | combination: HP and instantaneous water heater |
| Heat Pump        | SW 232 H3; 22,35 kW_{th}                      |
| Geothermal probes| 5 GTP each 100 m; distance: 6 m               |

For the refurbishment of the building, it is recommended to change to underfloor heating as the heat consumer. In addition, insulation of the floor on the first floor is carried out with the installation of underfloor heating. Depending on the maximum permissible drilling depth, a compromise must be found between a few geothermal probes, with large distances, and geothermal probes that are not too deep. According to current information, the simulation variant "Renovation FBH" is recommended. The roof, floor and exterior walls are insulated, the windows have double-pane thermal glazing, and the domestic hot water is provided by a fresh hot water station with a combined instantaneous water heater. The underfloor heating system is designed so that a maximum flow temperature of 35 °C is sufficient. This results in five geothermal probes, each 100 m deep, for the building. Table 5 gives an overview of the design of the plant technology. The addition of hybrid roof tiles for regeneration is recommended in principle [4,6]. For better efficiency, however, it is necessary to check to what extent the hybrid roof
tiles can be used for water heating and to what extent the surplus thermal energy is sufficient for regeneration. The energetic activation of the hybrid roof tiles provides for the generation and use of thermal energy (solar thermal) as well as electrical energy (photovoltaic) through the solar irradiation of the roof surfaces. The electrically activated areas by means of the hybrid roof tiles occupy about 13 m² each in their orientations to the northeast and southwest, and about 83 m² each in their orientations to the southeast and northwest. In total, therefore the annual output of the entire roof area is about 7750 kWh/a.

An advantage of the coupling of electrical and thermal activation is the increase of the efficiency of the PV modules, which can be increased if the modules are cooled. When coupled with the regeneration of geothermal probes, the thermal energy absorbed by the PV modules can be introduced into the ground. In conclusion, it can be said that energy optimization can also be carried out on listed buildings. Through careful planning in combination with dynamic building simulation and an intelligent combination of structural and plant engineering measures, the high potential from the interaction can be used and thus high energy savings can be made possible. Thus, a nearly climate-neutral building stock in historic preservation is feasible.

6. Experiences from the project up to now

To find an owner of an entire housing estate who is experienced as a builder of complex packages of measures in the existing building stock is certainly a rare starting situation, which made the implementation of the ambitious project much easier, if not possible in the first place. The commitment of the developer and the interest of the historic preservation authorities beyond the defined project are also advantageous. Nevertheless, the large number of participants, which is due solely to the size and nature of the estate, requires more intensive and time-consuming coordination than is probably needed in five individual properties for the implementation of renovation measures. The goal of testing the increased use of technologies and measures for energy optimization across the board, also in the listed buildings, requires an enormous amount of work for the preparatory studies and calculations as well as in the course of the necessary communication with the companies involved. But it is also important to involve the tenants of the occupied buildings in the ongoing research and development. In the course of the project, the attention of the research has thus shifted toward the needs of those involved. Under these conditions, the funding from the BMWi is the first opportunity to test and validate the range of investigations and measures on the comparatively small individual properties.

7. References

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