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TABSOLAR® – a novel approach of thermo-active (solar) building systems based on ultra-high performance concrete (UHPC)

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ABSTRACT

TABSOLAR® elements are novel (solar) thermal components made from ultra-high performance concrete (UHPC) which can be used as designable glazed or unglazed façade cladding elements or thermo-active building systems for heating and/or cooling. They are produced with an innovative production technology which is developed in a current research project together with appropriate system concepts. In order to simplify the system design process and visualize possible TABSOLAR® façades on site, new software tools are being developed. Finally, a demonstration façade will be installed on a renovated two-family residential building. The ongoing interactive design process of this first use case is an important part of the project and the overall TABSOLAR® concept.

Introduction

Environmental energy sources – sun, earth, air, water – will be the backbone of our future heating systems. Depending on the boundary conditions and their individual construction, the components capable of harvesting these energy sources can either directly provide useful temperatures or only low temperatures which can be raised to a useful level by heat pumps. The system seasonal performance factor (SPF_{sys}) of a heat pump system is the relation of the provided heat to the electrical energy needed to drive the heat pump and further pumps of the hydraulic system. Increasing the temperature of the heat source will increase the current coefficient of performance (COP) of a heat pump, and providing solar thermal energy will even allow times when it can be switched off. So, balancing the whole year, both measures can finally lead to an increase of the SPF_{sys} and thus to savings of electrical energy, which is important for the energy transition, since the fraction of renewable electricity is still far away from 100 % (e. g. around 50 % in Germany in 2022[1]). In contrast to fossil fuels which allow large storage capacities and thermal power in relatively small volumes and areas (neglecting the areas for gaining them), environmental energy sources basically feature much lower energy densities leading to large areas and volumes to harvest them. Therefore, apart from technical aspects, the development of appropriate components must consider the availability of areas as well as aesthetic aspects since the energy has to be provided on site or – in the case of district heating – as close as possible to the building to be supplied.

Numerous concepts of building-integrated photovoltaics (BIPV) or solar thermal (BIST) systems on different technology readiness levels (TRL) from prototypes to products have already been developed worldwide. The following exemplary approaches give an impression of the variety of solutions: [1] investigated an unglazed solar thermal collector for building façades based on a commercially available metal cladding façade system with serpentine tubes glued the absorber sheets, [2] focused on a loop heat pipe-based solar thermal façade water heating system. Various promising approaches exist; however, BIPV and – especially – BIST concepts are still niche markets despite a very high

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[1] https://energy-charts.info/charts/renewable_share/chart.htm?l=de&c=DE

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Nomenclature

COP	coefficient of performance [-]
F'	collector efficiency factor [-]
SPF_{sys}	system seasonal performance factor [-]
$\dot{Q}$	heating load [W]
T	temperature [K]
ΔT	temperature difference [K]
V_{stor}	storage volume [l]
$\alpha_{AM1.5}$	absorptance in AM 1.5 solar spectrum [-]
ε_{373K}	emissivity in spectrum of blackbody radiation at 373 K [-]
λ	thermal conductivity [W/(mK)]

potential both for new and existing buildings, in particular with respect to available façade areas of the building stock. The IEA SHC Task 41 investigated barriers concerning market penetration of the combination of solar energy and architecture. M. Wall et al. [3] identify a need for further developments concerning products, tools, and skills. They emphasize that it is important to increase the flexibility of products in terms of sizes, surface textures, colors, jointing and to provide additional dummy elements. Moreover, they state that many digital tools suitable for handling solar energy issues mainly address engineers working in an advanced design phase and tools for the early design phase (EDP) are lacking or not integrated in the normal workflow of architects. This is especially relevant since important decisions are already taken during the EDP.

Therefore, the TABSOLAR® concept described in this paper follows the hypothesis that it will not be sufficient to develop a novel product for (solar) thermal façades, but that a suitable "innovation ecosystem" comprising the overall workflow beginning in the early design phase and considering all relevant stakeholders is necessary as well. To reach this, an interdisciplinary consortium is essential. The final aim is to commercially establish complete TABSOLAR® solutions for sustainable buildings based on design tools, manufacturing technologies, materials, final products and services. This market perspective leads to various research questions some of which are tackled within this paper and thus are contributing to the scientific knowledge of applied solar energy solutions.

TABSOLAR® concept

Within the current German research project TABSOLAR III, which is funded by the Federal Ministry for Economic Affairs and Climate Action, a consortium of several research and industry partners works on the development of novel components from ultra-high performance concrete (UHPC) with integrated fluid channels. Ultra-high performance concrete (UHPC) is a material with a "high compressive strength of more than 200 MPa and an improved durability", offering a "variety of interesting applications" and allowing "the construction of sustainable and economic buildings with an extraordinary slim design" [4]. The so-called TABSOLAR® elements[2] can be used as solar thermal façade collectors in building envelopes or as thermo-active building systems for heating and/or cooling inside buildings (Fig. 1). Unglazed TABSOLAR® elements offer the possibility to use ambient heat and solar energy as a low-temperature source for heat pumps. Since both color and surface structure of the UHPC panels can be chosen, unglazed TABSOLAR® elements offer new design options for architects allowing to use them both as a façade cladding material and at the same time as thermo-active collectors. Other possibilities are given by glazed TABSOLAR® elements with spectrally selective coating which can provide higher temperatures and yields, comparable with standard solar thermal collectors. Fig. 2 shows three possible TABSOLAR® product families for different applications and design options. Inside buildings, TABSOLAR® elements act as thermo-active building systems (TABS) – either as stand-alone heating and/or cooling elements, especially in the ceiling, or in combination with concrete core activation [5]. In the latter case, the high thermal capacity of conventional concrete ceilings as an energy storage can be combined with fast-reacting TABSOLAR® elements. Due to the properties of UHPC, it is possible to produce slim and at the same time strong panels with a thickness of only 12 mm. The integrated bionic fluid channel structure based on the so-called FracTherm® algorithm [6] is directly formed from UHPC without any additional tubing.

The TABSOLAR® approach is not just a change from a conventional solar absorber material such as copper or aluminum to UHPC, but it is much more an interdisciplinary development process aiming at novel products for sustainable buildings considering architecture, façade design and construction as well as interior design. Hence, the development as a (solar) thermal component is based on these boundary conditions, which means that the consideration of material, fixing, design possibilities, etc. are important e. g. for the design of the collector, its construction, the spectrally selective absorber coating, etc. So, the challenge is to join both "worlds" of architecture and solar thermal [7] in order to create novel building products featuring specifications of design, construction and energy.

The overall aim of the TABSOLAR III project is to extend research and development from the core technology – the novel (solar) thermal elements – to system concepts and a suitable value chain from an early design phase via the production up to the final installation. Therefore, the TABSOLAR III project contains work packages on 1) new software tools for designers and architects, 2) components and systems and 3) a demonstration building. The following sections will cover some of the development steps and findings of TABSOLAR III.

New software tools: AR App and web configurator

Digitalization is revolutionizing the building and construction sector for many years. The European Commission has identified data acquisition, automating processes and digital information and analysis as the state of play of digitalization in the construction these days [8]. The effective use of data across the entire construction value chain and the involvement of stakeholders are key aspects to achieve significant benefits. While Building Information Modeling (BIM) is already utilized, Augmented Reality (AR) technologies have a high potential for the future. The need for decision support and visual feedback during the design phase has been identified in [9]. While users get real-time visual support, constraint-based algorithms solve the design problem. The authors of [10] identify configuration models as tools to improve the façade design. Barco et al. [11] call the configuration of envelopes on façades a mass customization problem. Product configurators are known as prime information systems to achieve mass customization due to the possibility to specify configurable products [12]. In [13] a modeling approach for configuration of modular building projects is given, and the lack of mass customization strategies in the building sector is identified. Furthermore, the application of product configuration and modularization principles in BIM can help to overcome challenges when applying BIM in the Architecture, Engineering and Construction (AEC) industry [14].

Hence, combining product configuration and BIM to achieve mass customization, involving all stakeholders across the value chain plays an important role for a revolutionary digitalization strategy in the construction sector. The TABSOLAR® configurator approaches these challenges by combining the web configurator TABSOLAR.Sales for sales, architects and planners and the AR App TABSOLAR.AR-Sales for customers to provide a holistic view for the stakeholders of building projects (Fig. 3). Both clients communicate with the configuration core TABSOLAR.Core, where the configurations are validated and the modular product knowledge can be accessed. The latter can be graphically modeled with TABSOLAR.Model by product managers for instance. After upload-

[2] With respect to a potential future product and/or company, TABSOLAR® is already a registered trademark.

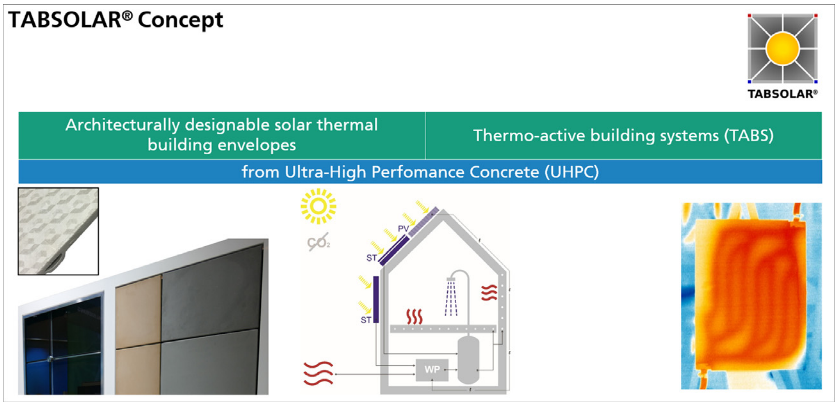

Fig. 1. TABSOLAR® concept: novel thermal components for building envelopes and interiors.

Three product families for different applications and design options

	TABSOLAR® Premium	*TABSOLAR® Economy*	*TABSOLAR® Design*
Glazing	anti-reflective	low-e	none
Coating	spectrally selective	lacquer or solid-colored	• None • lacquer or solid-colored • Spectrally selective weather-proof
Yields at medium temperature level/achievable maximum temperature	high	medium	low
Possible application	• domestic hot water preparation • solar combi systems	• domestic hot water preparation • solar combi systems	• domestic hot water pre-heating • low-temperature source for heat pumps • swimming-pool heating

Fig. 2. TABSOLAR® product families for different applications and design options.

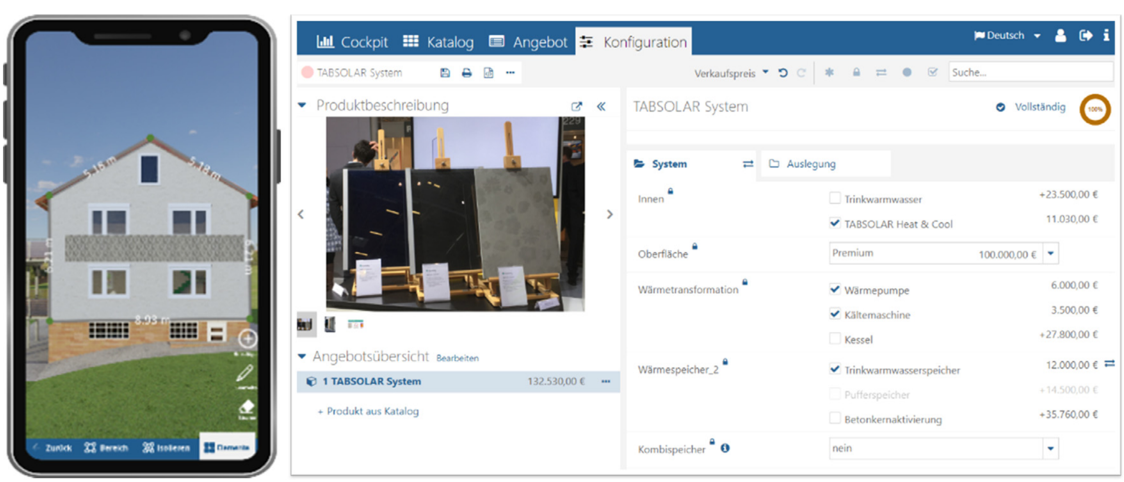

Fig. 3. TABSOLAR.AR-Sales AR App for the customer (left) and TABSOLAR.Sales web configurator (right).

ing the modeled product structure, rules and dependencies, the modular product knowledge is available to all clients.

TABSOLAR.Model, TABSOLAR.Core and TABSOLAR.Sales are based on the CAS Merlin CPQ which offers a complete toolbox for mass customization in any industry sector. On the one hand, TABSOLAR.Core connects to openBIM standards such as export to IFC files so that the data can be effectively shared across the value chain. On the other hand, it provides REST Service Interfaces to allow other applications to access data and functionalities (i.e. for the clients).

The AR App TABSOLAR.AR-Sales by TruPhysics connects to those interfaces, allowing a synchronous data exchange, which is necessary to depict a digital communication between customers and architects or planners. It is based on the ARCore framework and additional algorithms for placement, measurement and calculation. The app provides an intuitive and easy to use entry point for customers. They can use their smartphone to scan the façades of their building object via object detection, give initial preference or compare different solutions in an aggregated view to get first information and incentives to buy TABSOLAR®

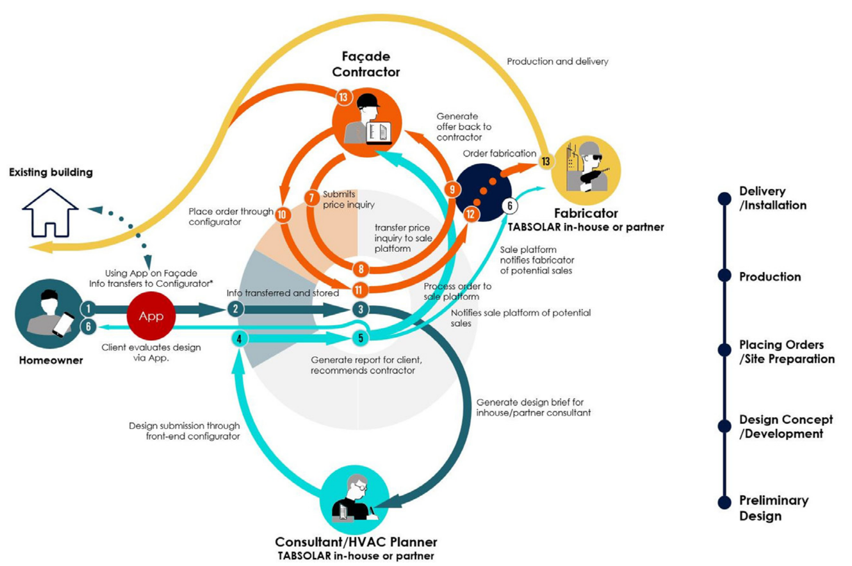

Fig. 4. Workflow of the TABSOLAR® use case building renovation.

solutions. When stored, the user input is taken to create a first product configuration on TABSOLAR.Core, making the data and configuration itself available for all other stakeholders.

Fig. 4 visualizes the whole use case of building renovation for the TABSOLAR® configurator, starting with the customer, the house owner, who uses a smartphone to scan the façades of an existing building via TABSOLAR.AR-Sales. TABSOLAR® elements can be virtually placed on the scanned façades to get an initial impression of the design, compare different product variants or see the impact on energy savings. Afterwards, the data is transferred and stored in the TABSOLAR.Core, so that consultants, architects or planners can access and augment the same configuration in the web configurator TABSOLAR.Sales or BIM, where further information can be stored. The matured version of the configuration can be used by fabricators and façade contractors to generate orders, for production or delivery, until the project is finished and the TABSOLAR® solution is delivered and/or installed.

Components and systems

TABSOLAR® elements

Design

Typical solar absorbers are built from thin metal sheets (copper or aluminum) with tubes attached to them by e. g. ultrasonic or laser welding. Changing from metal sheets with high thermal conductivities λ in the range of 220–380 W/(mK) and a thickness of less than 1 mm to UHPC with a thermal conductivity λ of only $2,66\frac{W}{mK} - 2,69 \cdot 10^{-3}\frac{W}{mK^2} \cdot T$ [15] and a thickness of several millimeters leads to the necessity of a different absorber design. Moreover, the TABSOLAR® concept follows the idea of an integrated absorber, which means that the channels are directly integrated in the absorber panel itself and not just attached as tubes. The differences between these absorber designs have been investigated in [16]. The collector efficiency factor F' is an important measure in order to assess the performance of a solar thermal absorber within the context of its surrounding, for example a collector casing. In [17] F' of several commercially available solar thermal absorbers has been determined by measurements, leading to values between 0.81 und 0.97 (depending on construction, especially the channel distance, and the fluid flow). In [15] it could be shown by numerical simulations that despite the low thermal conductivity of UHPC F' values in the range of 94.4 to 97.7 can be reached (depending on the panel thickness and channel distance) since smaller channel distances and thicker panels had been assumed. Concerning the channel distance, it has to be kept in mind that the bionic FracTherm® algorithm had been chosen to design the fractal-like channel pattern featuring numerous bifurcations following each other. This leads to the fact that the number of parallel channels in the middle of the absorber is always 2^n with n being the number of iterations of the FracTherm® algorithm and therefore the channel distance cannot be chosen arbitrarily. When defining an appropriate size of the TABSOLAR® elements, many aspects – some of them being contrary to each other – have to be considered (the mentioned numbers are related to a panel area of about 1–2 m^2):

- handling on the building site (elements as small and light as possible)
- small thermal boundary losses (elements as large as possible)
- costs for hydraulic connections (elements as large as possible)
- number of FracTherm® channels: 16 or 32
- distance between FracTherm® channels as small as possible, but not less than about 40 mm (else geometric problems will occur)
- border areas without channels to be able to place agraffes or collecting channels
- appropriate aspect ratio

Finally, a size of 1683 mm x 1040 mm was chosen for the TABSOLAR® elements. These dimensions lead to a gross area of 1,75 m^2, an aspect ratio following the “golden section”, a channel distance of 54,4 mm from center to center (with 16 channels) and a weight of 50 kg. Before producing large TABSOLAR® elements on a production plant, it was intended to test and adjust the production technology based on the membrane vacuum deep-drawing process described below (section “Production” and Fig. 7) with a small-scale sample plant. It was decided to keep one of the dimensions and produce square elements with dimensions of 1040 mm x 1040 mm. The FracTherm® algorithm is capable of creating multiply branched channel designs on a given area which does not have to be rectangular. If it is rectangular, the algorithm partially leads to channels with negative slopes (relative to flow direction). Since it is intended to operate *TABSOLAR® Premium* elements in solar drainback systems, it is important that the elements are fully emptied when the pump is switched off. However, negative slopes would lead to a remaining volume in the channel parts below the FracTherm® inlet channel. Therefore, it was necessary to adjust the boundary form of the area on which the channel design had to be generated and thus “force” the algorithm to generate channels with positive slopes only (Fig. 5). Fig. 6 shows the FracTherm® channel designs for large and small TABSOLAR® elements considering border areas for agraffes and collecting channels.

Production

TABSOLAR® elements are produced using the membrane vacuum deep-drawing process invented by Fraunhofer ISE and further developed with project partners within TABSOLAR [15], TABSOLAR II [18] and the current project TABSOLAR III. The main idea of the process is to create

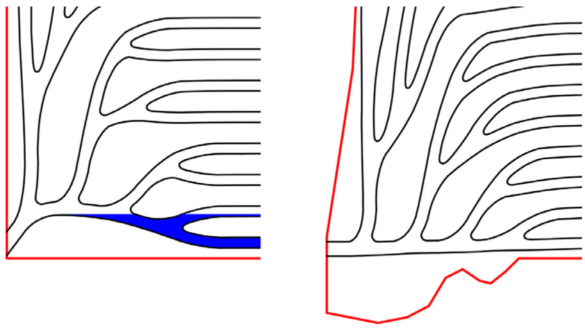

Fig. 5. Creation of FracTherm® channel design: rectangular area leads to negative channel slopes and thus remaining fluid (left), adjusted boundary form "forces" algorithm to create positive channels slopes in order to ensure full emptying (right).

elements with integrated channels directly from UHPC without needing casting cores. The basic principle of the process (Fig. 7) consists of the following steps:

1 UHPC is casted onto a membrane located on top of a mold containing the channel design. At the same time a flat plate is casted in a separate mold.
2 The volume beneath the membrane is evacuated, thus both the membrane and UHPC are formed according to the shape of the mold.
3 The vacuum mold is turned upside down and joined with the mold of the flat plate. At this time, the UHPC is still viscous.
4 After hardening, the TABSOLAR® element can be demolded.

UHPC is usually a high fineness concrete, which is outside the usual standard and concrete strength classes and is defined with strengths above 140 MPa. In G.tecz' opinion, defining a UHPC in terms of strength is not sufficient or authoritative, because the term "performance" encompasses much more than just compressive strength. Rather, it is properties with regard to the

- flexural strength
- structural integrity
- durability
- flow properties
- surface properties
- haptics
- density
- thermal conductivity
- application of standard raw materials
- fiber modification
- cement quantities
- and much more

that characterize a UHPC and define and contribute to its performance.

Thus, the most different fresh and hardened concrete properties of UHPC can be adjusted or "programmed" by the appropriate selection and composition of the raw materials. G.tecz Engineering GmbH is a research and development service provider and is engaged in the development of various mix formulations of hydraulically bound high-performance materials within the scope of its own research and development as well as customer-specific and publicly funded projects. For the production of TABSOLAR® elements a mix formulation was developed which can be deep-drawn in the fresh state and is thus suitable for the formation of flow-through channel structures.

The basis for the development of compound formulations and the selection of suitable starting materials is the calculation of the respective packing density, taking into account the optimum water film thickness (Fig. 8) [19].

In the case of a dry blend of particles with different particle diameters and distribution, there is a cavity between these individual particles which is called an interparticular space. In this case, the dry mix is not filled with water yet and the individual particles are in point contact. During the mixing process of the concrete, water is added to the dry mix. Here, the particle surfaces are first wetted and the interparticular space will be filled with water. To enable workability of the fresh concrete, the interparticle friction across the contact points of the individual particles must be reduced and thus a spacing between the particles must be achieved. As a result of further water addition, a water film with a defined thickness can be built up and adjusted around each particle. The surrounding thickness of the water film is referred to as the water film thickness. Depending on the water film thickness (larger or smaller) and the optimization of the packing density, i.e. filling of the interparticle space, the rheological properties of the fresh concrete as well as the hardened concrete properties are influenced and optimized.

By selecting and using suitable raw materials and adapting the water film thickness, the rheological properties of the fresh concrete can be influenced and "programmed" for the desired application.

The developed mix design was adapted to the current production process and tested at G.tecz on a small-scale sample plant (SSSP). The SSSP is used to test the process and to investigate and optimize process sequences that are necessary for a semi-automated production plant which is being built by project partner Wendt Maschinenbau GmbH & Co KG. The TABSOLAR® elements produced on the SSSP have a size of 1040 mm x 1040 mm, include bushes for hydraulic connectors and – for the product family *TABSOLAR® Design* – can be freely adapted to the architectural requirements in terms of the exposed concrete surface.

Due to the developed mix composition, the used fines as well as the limitation of the maximum grain size, a wide variety of surfaces from smooth/glossy to filigree structures to distinct topological struc-

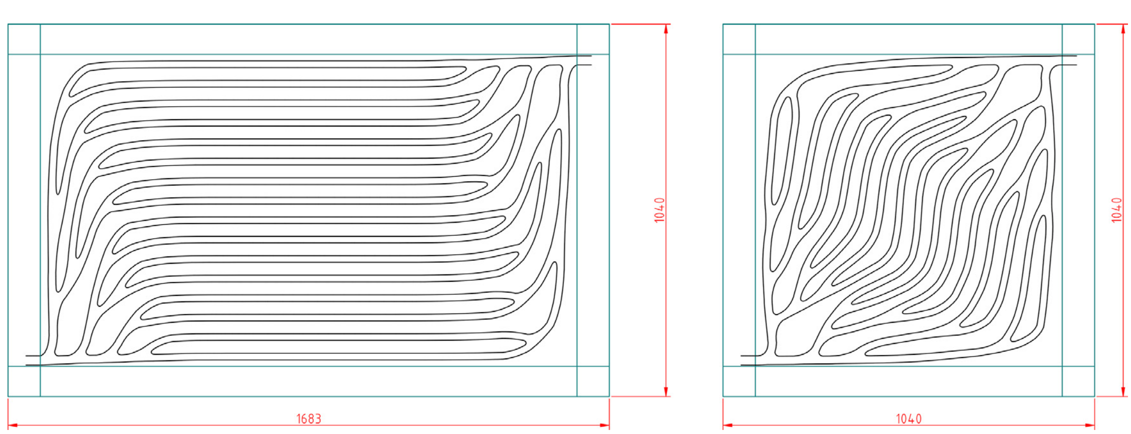

Fig. 6. FracTherm® channel designs for large TABSOLAR® element (left, 1683 mm x 1040 mm) and for small TABSOLAR® sample (right, 1040 mm x 1040 mm) with border areas for agraffes and collecting channels.

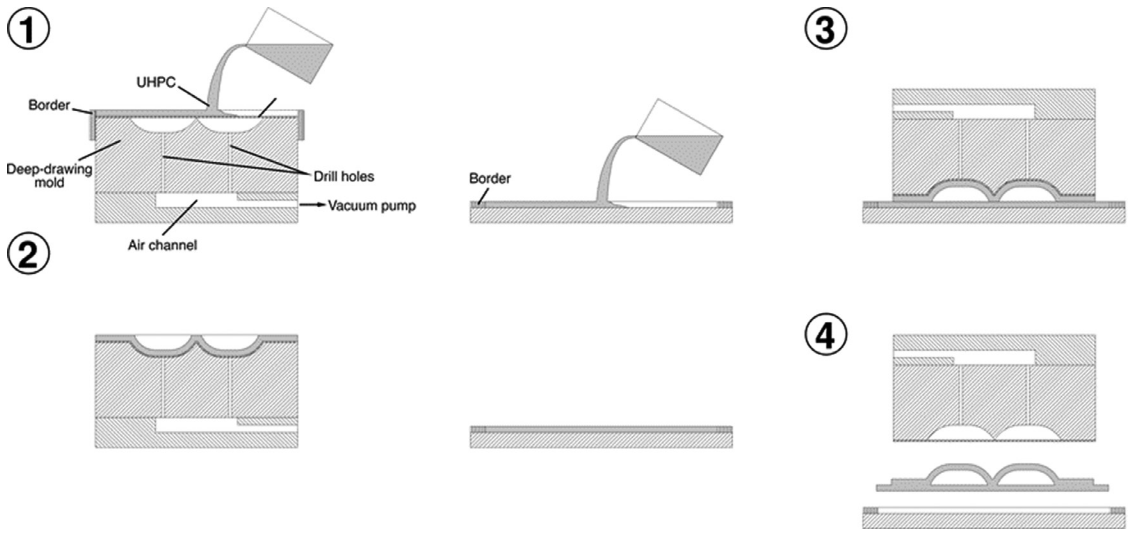

Fig. 7. Basic principle of membrane vacuum deep-drawing process (details and further developments not shown).

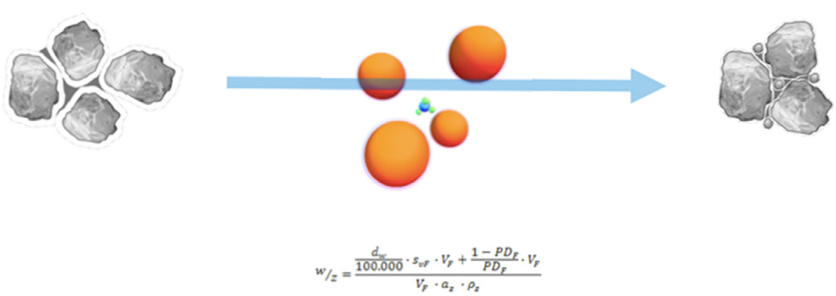

Fig. 8. Calculation and optimization of packing density and water film thickness [19].

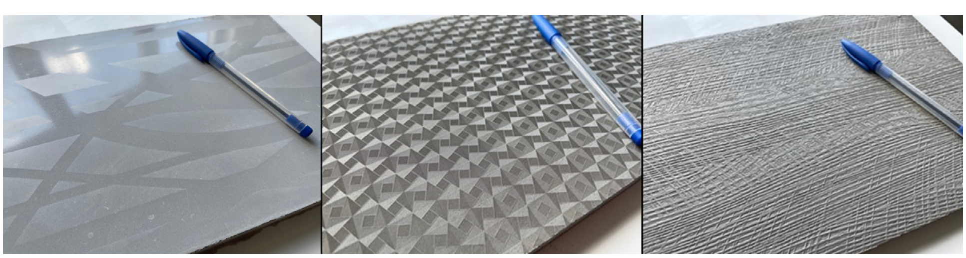

Fig. 9. Different surfaces of casted UHPC: matt/glossy (left), relief/microstructure (center), wood texture (right).

tures can be reproduced using shuttering matrices made of silicone or polyurethane rubber (Fig. 9). These materials are also used as mold material in the SSSP.

After many experiments which had been carried out in TABSOLAR and TABSOLAR II it had become obvious that the joining process of the membrane vacuum deep-drawing process had to be adjusted, since it had turned out that often some channels had been closed by UHPC or that the two halves had not been connected. Within TABSOLAR III, an adjusted joining process had been tested at laboratory scale at Fraunhofer ISE and then transferred to G.tecz, who set it up in the small-scale sample plant. Based on the 2D FracTherm® channel design, molds had been constructed in CAD. In Fig. 10 the milled mold for the production of small TABSOLAR® samples (1040 mm x 1040 mm) is depicted; Fig. 11 shows the CAD drawing of the mold for the large TABSOLAR® elements (1683 mm x 1040 mm) intended to be installed in the demonstration façade.

The SSSP uses an electrically driven and controlled belt and roller conveyor on which the formwork parts are filled with fresh concrete in the direction of production. In the process, the fresh concrete is applied to the formwork by means of a concrete pump via a linear axis, and the concrete is scraped off at a defined height using vibration energy. The

Fig. 10. Milled mold for membrane vacuum deep-drawing process (1040 mm x 1040 mm).

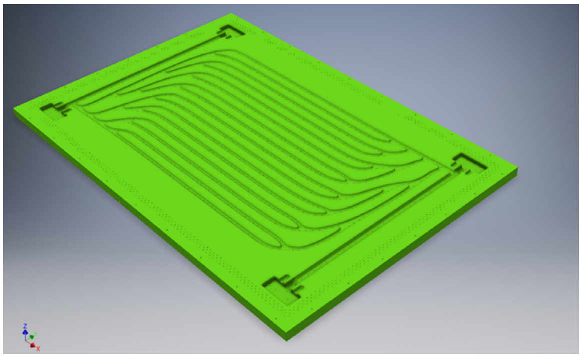

Fig. 11. CAD drawing of mold for membrane vacuum deep-drawing process (1683 mm x 1040 mm).

definable fresh concrete layers produced in this way are fed to a subsequent process step in which the fresh concrete is deep-drawn in one of the two mold halves to form the channel structures. After preparation of the channel connection points, the deep-drawn mold half is lifted and turned upside down into the opposite and aligned visible side. This is followed by the joining process in which both fresh concrete halves are joined together. The joining of the two fresh concrete halves thus takes place fresh in fresh, and both fresh concrete halves form a chemical bond. This allows to dispense with an adhesive joint and adhesive, which in turn has a positive effect on the CO_2 balance. Furthermore, the absence of an adhesive supports easy recycling of the TABSOLAR® elements at the end of their lifetime and can be disposed of as construction waste. Fig. 12 and Fig. 13 show work steps of the small-scale sample plant.

Several TABSOLAR® samples have been produced by G.tecz with the SSSP, and the production process is continuously being improved. The TABSOLAR® sample in Fig. 14 features vertical collecting channels on the right and on the left allowing to connect several samples to each other using metallic hydraulic connectors with O-ring sealings inserted into cylindrical bushes at the ends of each collecting channel. Fig. 15 shows cross sections of TABSOLAR® samples as well as a cylindrical bush for hydraulic connectors.

Spectrally selective coating

Spectrally selective coatings are state of the art of conventional solar thermal absorbers. However, it is a challenge to apply durable coatings with high absorptance in the solar spectrum and low infrared emissivity on UHPC as surface roughness and porosity are quite different compared to standard substrates used for PVD coatings like polished metal or glass. Also, water vapor diffusion needs to be suppressed. At Fraunhofer ISE a coating system consisting of a base lacquer, a sputtered selective coating and a cover lacquer has been developed and assessed with respect to water vapor permeability (gravimetric) according to DIN 53122. The test had been carried out at a temperature of 70 °C and a relative humidity of 10 %. Fig. 16 shows the reflectance vs. wavelength of the small UHPC sample with the spectrally selective coating between lacquer coats. As is typical for spectrally selective coatings, the curve shows low reflectance (i.e. high absorptance) for short wavelengths in the solar spectrum and high reflectance (i.e. low emissivity) for long wavelengths in the infrared spectrum. The absorptance $\alpha_{AM1.5}$ is in the range of 94 %, the emissivity $\varepsilon_{373\ K}$ about 7 %, which is quite close to typical values of commercial solar thermal absorber coatings on metals ($\alpha_{AM1.5} \approx 95 - 97$ %, $\varepsilon_{373\ K} \approx 4 - 5$ %)[3]. Moreover, it can be seen that there are only minor changes of the curve after accelerated aging, which means that the coating system is durable.

Thermal shock resistance

UHPC has not yet been used for solar collectors or thermally activated building systems. It is well known that the use of concrete is suitable in a wide temperature range, and heating above ambient temperature can even increase the compression strength by drying effect [20]. Above 300 °C, which is much higher than the temperatures in our collector, a decrease in mechanical characteristics is expected [21]. Despite the suitability of UHPC in the collector's temperature range, its thermal shock resistance had to be proven. Thermal shock resistance is the ability to resist rapid and sudden temperature changes. A thermal shock can occur after stagnation and idling, when the colder fluid flows back into the heated collector. A temperature difference ΔT of 130 K is assumed to be the worst case. The influence of thermal shock on the load-bearing capacity of UHPC was experimentally investigated. Therefore 7 mm thick UHPC plates were cut into 20 mm wide strips, heated to 150 °C or 280 °C and quenched in 20 °C cold water. There were no visible cracks after quenching, neither with the naked eye nor under a 10x magnifying glass. Only under the light microscope superficial cracks could be identified (Fig. 17). Thereby, the higher heated specimens showed more and larger cracks, and also the rough sides showed more cracking than the smooth ones.

After the temperature shock, the quenched and also the untreated reference specimens were loaded with a loading speed of 1 mm/min in a three-point bending test (Fig. 18) until failure. Since the surfaces of the two sides of the plate differ significantly due to the manufacturing process, attention was paid to the load direction in the test and distinction was made between tension on smooth and rough side.

Fig. 19 shows the determined bending strengths. The measured strengths are higher on average if the smooth specimen surface is on the tensile side of the bending than if the rough side is subjected to tensile loading. In addition to the notch influence of the roughness, a manufacturing-related increase in the number or size of the pores from the smooth to the rough side is also conceivable as a cause for this. No significant strength reduction due to thermal shock was found, which means that the UHPC is thermo-shock resistant in the investigated temperature ranges and differences, which are much higher than they will occur in operation.

TABSOLAR® systems

Sizing and performance prediction

Both in the TABSOLAR® configurator and in the TABSOLAR.AR-Sales app, calculation methods are implemented that process the design-relevant parameters of the system. This requires methods that map the interaction of different parameters in a simplified way and provide dynamically adaptable results quickly. A first result on the achievable performance should already be provided in the app based on a few input values. A much more detailed calculation is performed in the configurator; here, the inputs are specified in more detail and decisions in the design process, in particular the dimensioning of heat pump and storage tank, are addressed.

The basis for the information processing in the app is an approach whose core is a so-called *system design map*. The most important aspects [22] (*façade design, costs and efficiency*) are linked; the dimensions and orientation of the unglazed (uncovered) and glazed (covered) active areas are central to this. An advantage of the method presented here is the *bi-directional planning entry option*: It is possible to either specify the system efficiency to be achieved or to start with a façade layout or cost boundary condition.

In this way, it is possible to make the technical, economic and design issues in the planning process of a TABSOLAR® system easily accessible to the user.

[3] https://alanod.com/de/produkte/unsere-oberflaechen/absorptionsoberflaechen, https://docplayer.org/106486982-Produktspezifikation-tinox-energy.html, https://solab-solar.com/das-herzstueck-ihres-kollektors-der-absorber/

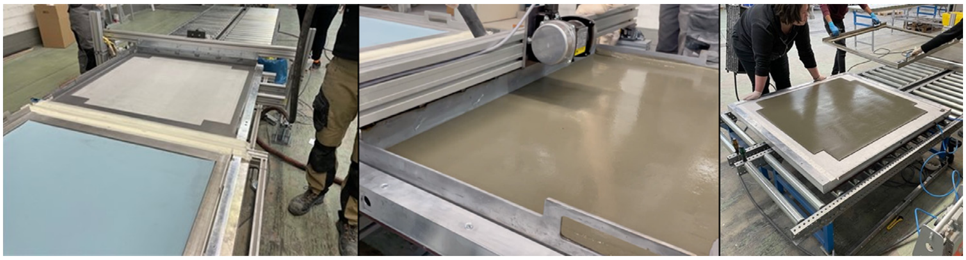

Fig. 12. Small-scale sample plant: molds and material application (left), application of fresh concrete (center), fresh concrete layer prepared for deep-drawing (right).

Fig. 13. Small-scale sample plant: molds prepared to be joined together (left), turning the deep-drawn formwork (center), positioning before joining (right).

Fig. 14. TABSOLAR® sample (1040 mm x 1040 mm) produced with small-scale sample plant (top), cross-section (bottom).

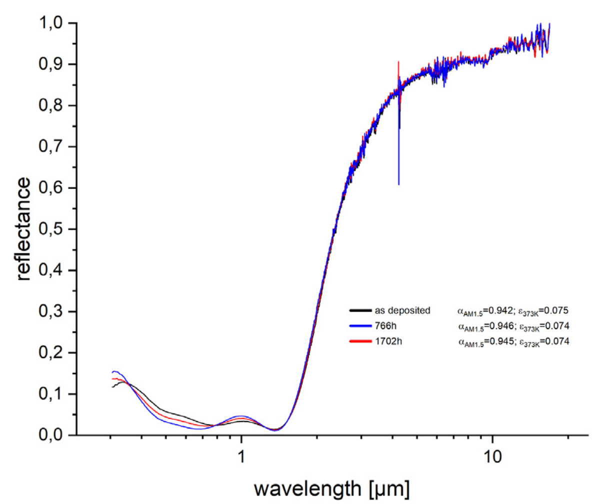

Fig. 16. Reflectance vs. wavelength of small UHPC sample with spectrally selective coating between lacquer coats.

Data basis: detailed system simulations with Polysun

In order to analyze the behavior of the elements and the interactions within a complete supply system, different constellations were investigated with the simulation software *Polysun (Vela Solaris)*. These results

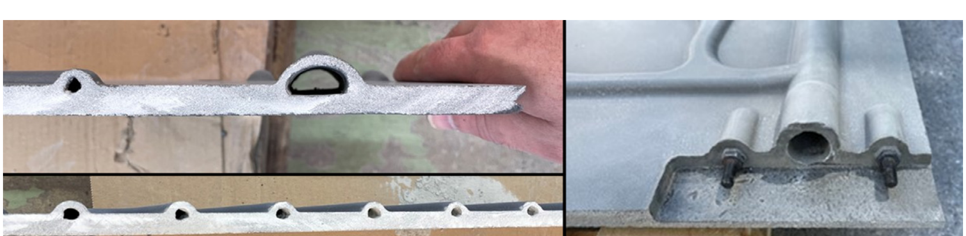

Fig. 15. TABSOLAR® samples: cross sections (left top and bottom), cylindrical bush for hydraulic connectors (right).

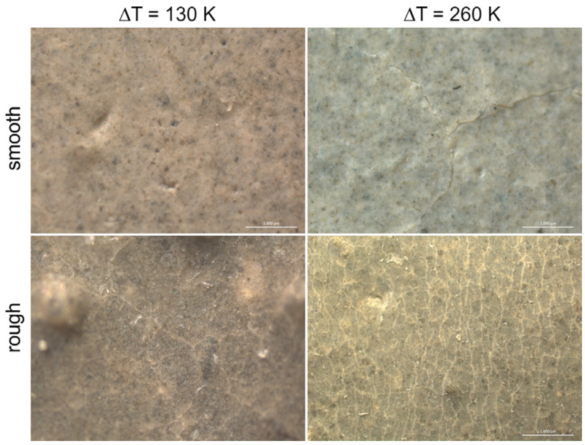

Fig. 17. Surface cracking due to thermal shock (light microscope).

of the detailed simulation form the data basis. The research task is to make these results as easily usable as possible for the planning process in order to fulfill the described development goals of the software. The aim is to limit the complexity to the essential interrelationships and still maintain the highest possible flexibility and accuracy.

For the results shown as an example at the end of the section, *TABSOLAR® Design* serves directly as a heat source for a heat pump; optionally, the collector circuit can be extended by a brine buffer or coupled with an ice storage tank, which, however, will not be discussed in detail here. Between the heat pump and the hot water storage tank a hydraulic switchover system is installed for charging at the domestic hot water and heating temperature level. *TABSOLAR® Premium* charges the hot water storage tank directly; a heat exchanger is connected in between, which connects the secondary circuit (via the charging lance) with the drain-back system. On the source side, the heat pump is equipped with a three-way valve; by mixing with the colder fluid leaving at the evaporator, the source inlet temperature is limited to prevent a high pressure (first type) failure. Fig. 20 shows the corresponding hydraulics.

TABSOLAR® Premium elements are equipped with an insulation layer on the rear face to minimize thermal losses at high temperatures similar to conventional solar thermal collectors. However, the uncovered *TABSOLAR® Design* elements are modeled as a rear-ventilated façade. The results of Fraga et al. [23] show that an insulation on the rear face of uncovered elements on the source side of a heat pump does not result in higher system seasonal performance factors, as the lower efficiency in winter due to the reduced heat exchange with the ambient is dominating.

Development of a system design map

Both from an energy point of view and from the architect's perspective, the *thermally active façade surfaces*, their *orientation* and the *product family* (*TABSOLAR® Premium | Economy | Design*) have the biggest influence on the configuration. In the technical system, there are two interfaces to the environment that determine the achievable performance: on the one hand, the quality of the heat source, and on the other hand, the potential of the solar thermal absorber system. This leads to the approach of summing up all influences to two central specific variables and assigning a performance indicator to them in a two-dimensional map. The *system seasonal performance factor* SPF_{sys} (ratio of the heat quantity provided over a year and the electrical energy used: heat pump + circulation pumps) is used as the overall performance indicator. The *specific uncovered source area* (*TABSOLAR® Design*) is plotted on the horizontal axis, the *specific glazed area* (solar thermal, *TABSOLAR® Premium*) on the vertical axis. To be able to provide results for systems of different sizes, the areas are related to the maximum *heating load*.

The conversion of different orientations into south-equivalent areas is an important simplification step in the calculation process. The corresponding factors were determined empirically from the comparison of simulation results for different orientations; those constellations are called equivalent which lead to the same annual performance result. For both the uncovered (source) and the glazed elements (solar thermal), a symmetrical pattern is seen when deviating from the best orientation to the east and west; while south is the best possible orientation in the first case, the maximum in the second case is shifted to -10° in the eastern direction. This can be explained by the more favorable temporal relationship between load and yield in the daily profile.

The first results of the analysis show that the influence of the orientation for the solar thermal system and for the source can be represented to a good approximation with a constant factor, which is independent of the specific areas. For typical design cases, the maximum deviation (system seasonal performance factor) of the results compared to the simulation with detailed mapping of the orientations is about 4 %.

Example

For the scenario of a renovated one- or two-family house with low-temperature panel heating and heat pump, which is designed as a monovalent system without a heating rod, the system design map shown in Fig. 21 represents the results of the system simulations. As boundary conditions on the sink side, a domestic hot water tap temperature of 45 °C and for the floor heating a design spread of 35 °C/28 °C were assumed; on the source side, a direct integration without storage tank was modeled, corresponding to the hydraulic diagram in Fig. 20.

In a comparison simulation, a monovalent system with an air heat pump without solar thermal support achieves a seasonal performance factor of about 4.3. This value, which is quite high in comparison with real systems, is partly due to the assumed low supply temperatures and partly the result of the optimized control in the model [24]. Independently of this, this comparison shows that per kW of heating load about 3.7 m^2 of source area, covered with *TABSOLAR® Design* elements, is required to represent a source of the same quality as ambient air. If the façade orientation deviates from south, this value increases according to the gray lines in the lower blue area of the system design map.

The dashed arrows correspond to the following example configuration:

- maximum heating load $\dot{Q}$: 10 kW
- source: *35 m^2 uncovered TABSOLAR® Design* elements on SE façade (-55°)
- solar thermal: *40 m^2 glazed TABSOLAR® Premium* elements on SW façade (Δ 45°)

For the described system, under the mentioned boundary conditions, an expected system seasonal performance factor SPF_{sys} of 5.5 and a

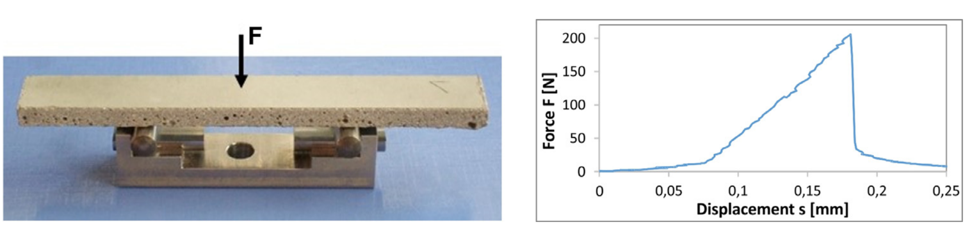

Fig. 18. UHPC specimen and device for three-point bending test (left) and a typical force-displacement curve (right).

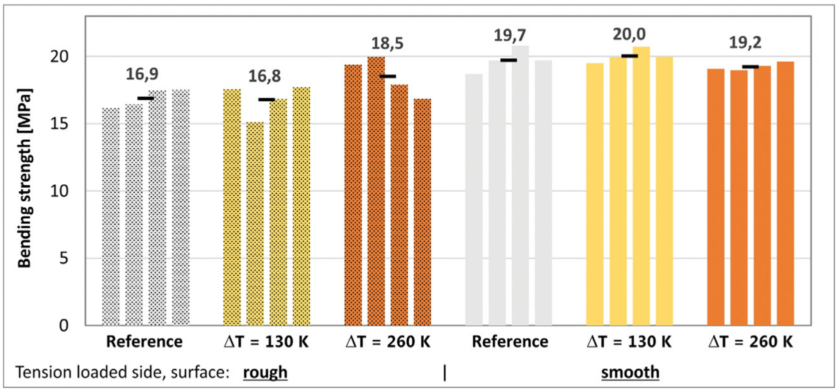

Fig. 19. Bending strengths of reference and quenched specimens (4 samples each and mean value).

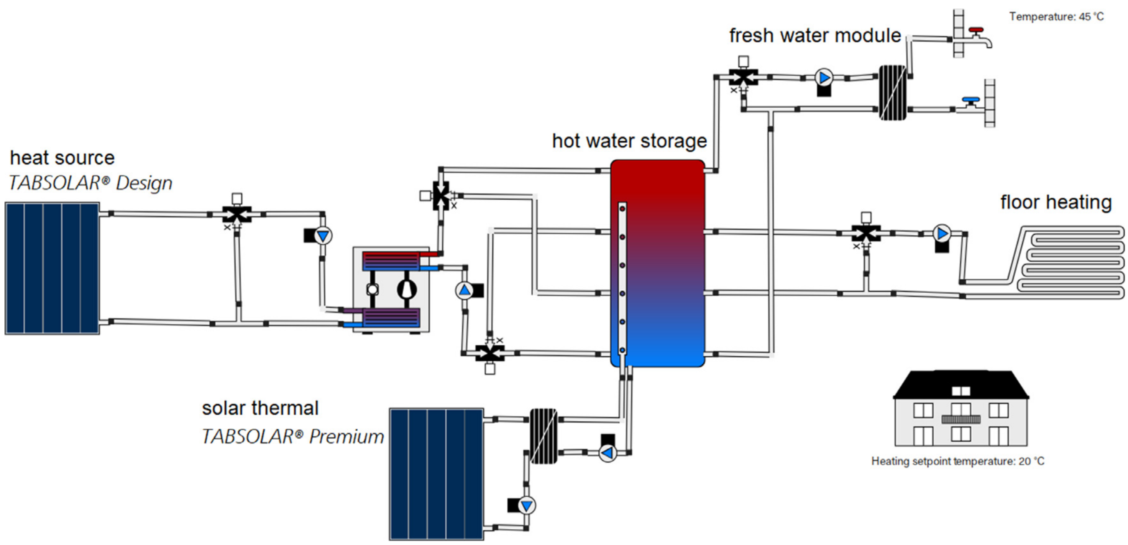

Fig. 20. Hydraulics of the simulated system.

suggested hot water storage size of V_{stor} = 1700 liters (170 liters/kW) is the result.

Several system design maps are needed to obtain results for different building scenarios; however, in line with the first results, they differ little in quality.

Further investigations on the energetic and ecological potential of TABSOLAR® elements are given in [25].

Demonstration building

An important aspect of the TABSOLAR III research project is the realization of a demonstration façade within the framework of an actual construction project. The aim of this implementation is to verify the feasibility of applied TABSOLAR® elements, being designed as façade cladding with integrated FracTherm® channel structure for collecting solar thermal energy. In addition, insights into the technical requirements and the interaction of various necessary stakeholders during planning, production and installation are gained. In order to estimate the energy performance of the TABSOLAR® demonstration façade, a long-term monitoring will be conducted during the subsequent building operation, also for being able to assess the energy potential for similar future façades.

The use case is the renovation of a two-family house from the 1960s in Kassel, Germany. The renovation measures cover the renewal of the heating system as well as the additional insulation of exterior walls by an ETICS (External Thermal Insulation Composite System). As shown in Fig. 22, an area was excluded from the ETICS on the south-east facing wall to leave space for a rear-ventilated façade with the integrated TABSOLAR® elements. With the possible yields from solar energy harvesting, TABSOLAR® is intended to contribute to the building's energy concept and its sustainable operation.

Both product families *TABSOLAR® Design* (unglazed) and *TABSOLAR® Premium* (glazed) are applied in the demonstration façade implementation. A total of five *TABSOLAR® Premium* elements, which have a spectrally selective coating and an additional glass cover, are arranged vertically above each other in the center of the wall according to Fig. 23. In addition, there are 14 *TABSOLAR® Design* elements distributed on the surface, which are visually distinguished by the exposed UHPC concrete surface. Essential parameters for planning the layout of the façade were the available areas of the stock façade with existing window openings as well as the predefined dimensions of 1683 mm x 1040 mm of the TABSOLAR® elements. Another aspect is the piping of the system. All elements are connected to each other through flexible pipes, which also connect the entire system with the building services. As the integrated fluid inlets and outlets are positioned on the bottom and top of the panels, a vertical arrangement of interconnected TABSOLAR® elements is required. Remaining areas, especially at the edge regions around the windows, are lined with simple UHPC elements without integrated piping. Aluminum cladding closes the overall structure at the bottom and top, as well as at the interfaces to the ETICS on both sides.

The construction of the demonstration façade is based on a substructure that is mounted on the stock wall. An on-site survey by a local civil engineer revealed that the existing wall consists of porous hollow

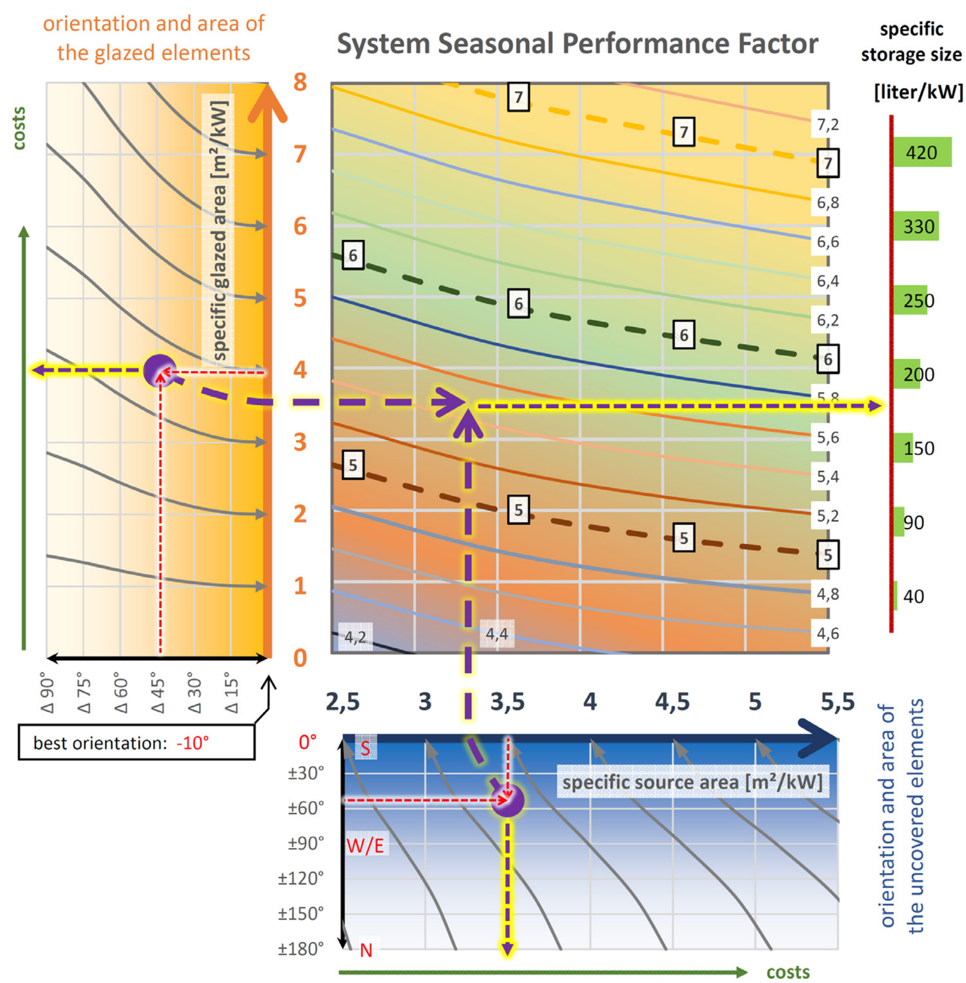

Fig. 21. System design map with sample configuration.

Fig. 22. Existing building of the renovation project in Kassel, Germany.

Fig. 23. Visualization of the demonstration façade.

blocks that are unable to directly support the loads of the demonstration façade. For this reason, additional concrete post foundations are inserted into the wall as shown in Fig. 24, to which the substructure is attached via U-brackets. These load-bearing U-brackets are supported by additional ones, directly mounted into the wall to only compensate horizontal forces.

The substructure itself consists of vertical profiles on which horizontal traverses are mounted. Fig. 25 shows the arrangement of the profiles in the overall system of the demonstration façade. The intermediate areas are filled with 180 mm thick thermal insulation. Depending on the product configuration, the TABSOLAR® elements are hooked into the traverses at a distance of approximately 50 mm from the thermal insulation via agraffes as visible in Fig. 26. *TABSOLAR® Premium* elements consist of an additional insulation as part of the panel, filling the cavity behind the element. In both cases, the agraffes are fastened to the TABSOLAR® elements invisibly from the outside via undercut anchors. Within the scope of the demonstration façade project, various pull-out tests of the undercut anchors were carried out to verify the integrity of

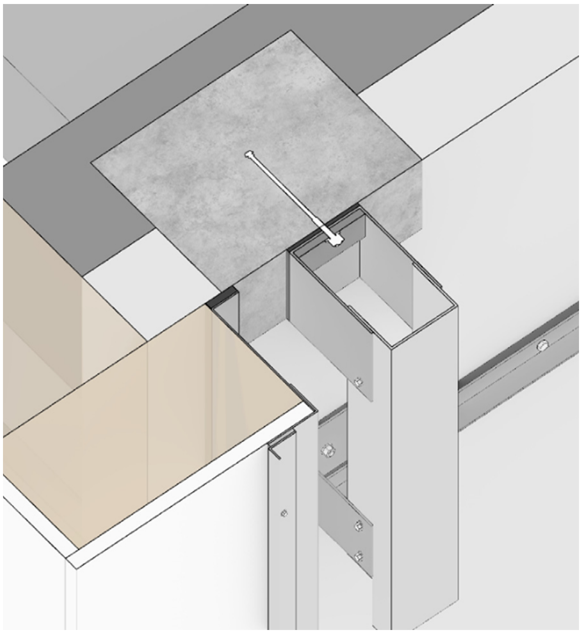

Fig. 24. Concrete posts as a foundation for the substructure.

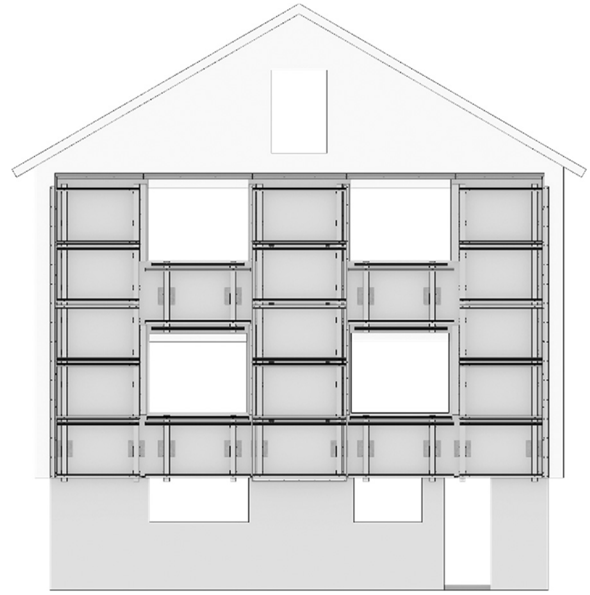

Fig. 25. Layout of the vertical profiles and traverses.

the connection, especially in light of the special liquid-bearing UHPC elements in this application. Fig. 26 shows the overall structure of the construction with the substructure on the left, the TABSOLAR® elements equipped with agraffes in the middle and the additional glass cover for TABSOLAR® *Premium* elements on the right.

Another planning task was the collision-free piping of the system. It was integrated into the façade in joint coordination between Fraunhofer ISE and Priedemann Fassadenberatung GmbH, as being responsible for the substructure. It was a challenging task to plan the interconnection between TABSOLAR® elements separated by windows in between, since the piping had to follow a three-dimensional path. In the resulting construction, the traverses serve not only as their primary function as TABSOLAR® element holders, but also as holding points for the piping. Fig. 27 shows the piping system integrated into the substructure.

The application in the context of a building renovation results in special requirements for the planning of the demonstration façade. In addition to the building-dependent arrangement of the elements, also deviations and inaccuracies had to be considered, as well as tolerances at the interfaces to refurbishment measures of other trades involved. For this reason, an as-built survey of the façade was carried out, and the results were integrated into the 3D planning of the façade as documented in Fig. 28.

Up to now, small TABSOLAR® elements (1040 mm x 1040 mm) have been produced on a small-scale sample plant and will be tested under laboratory conditions. The implementation of the demonstration façade is therefore a first-time application of TABSOLAR® elements in a real construction project. This results in further risks for the implementation of the demonstration façade, which are countered by the preliminary implementation as a test rig. The test rig corresponds in its structure to the implementation of the actual demonstration façade, but only shows a section of three small *TABSOLAR® Premium* elements that will be produced on the small-scale sample plant. The elements will be installed with the substructure on a mounting wall at Fraunhofer ISE. In addition to validating the design principle, the test rig also serves to test the interaction of the partners involved in the project, as well as the assembly processes in the implementation of the actual demonstration façade.

After completion of the design planning, the project is now in the stage of preparing the fabrication with subsequent procurement of all necessary parts and components. According to current time planning, the substructure of the façade will be implemented by end of 2022, while the demonstration façade is expected to be fully completed in spring 2023 by installing all TABSOLAR® elements.

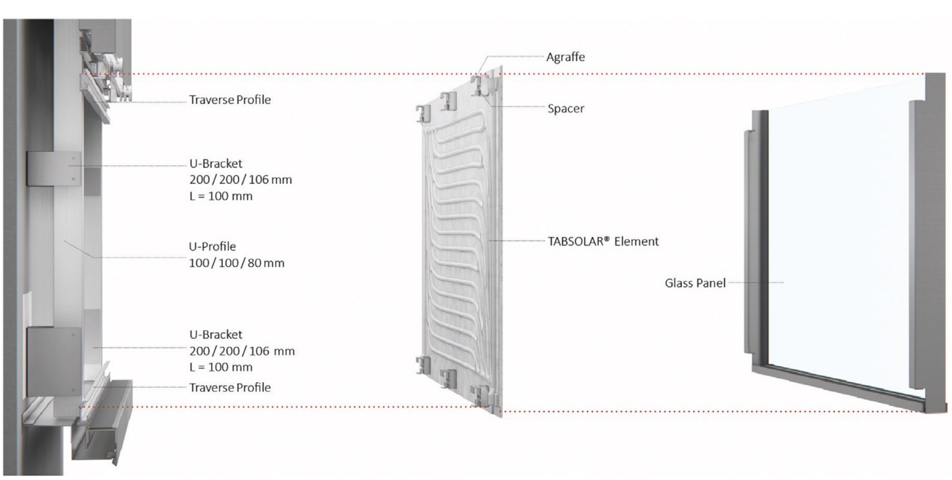

Fig. 26. Exploded view of the TABSOLAR® demonstration façade structure.

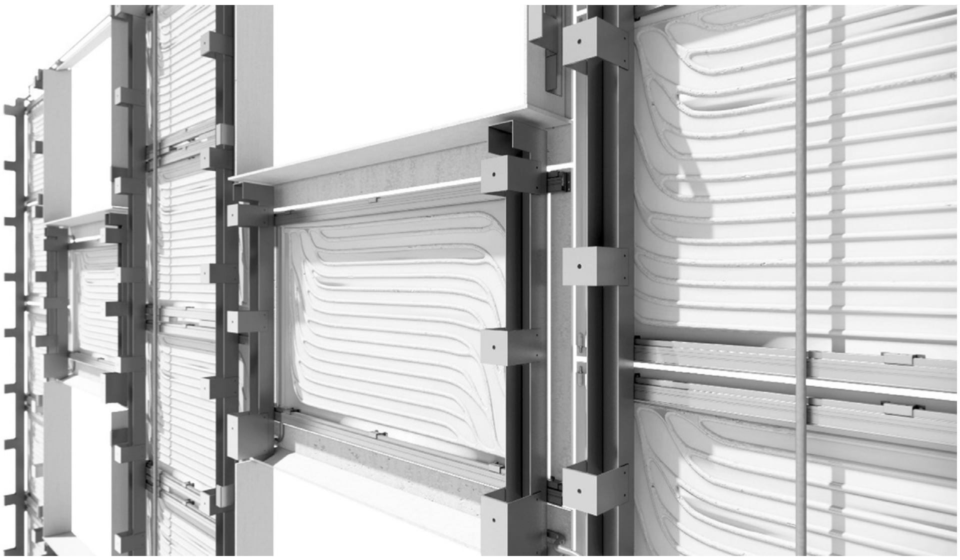

Fig. 27. Rear view of the structure with integrated piping.

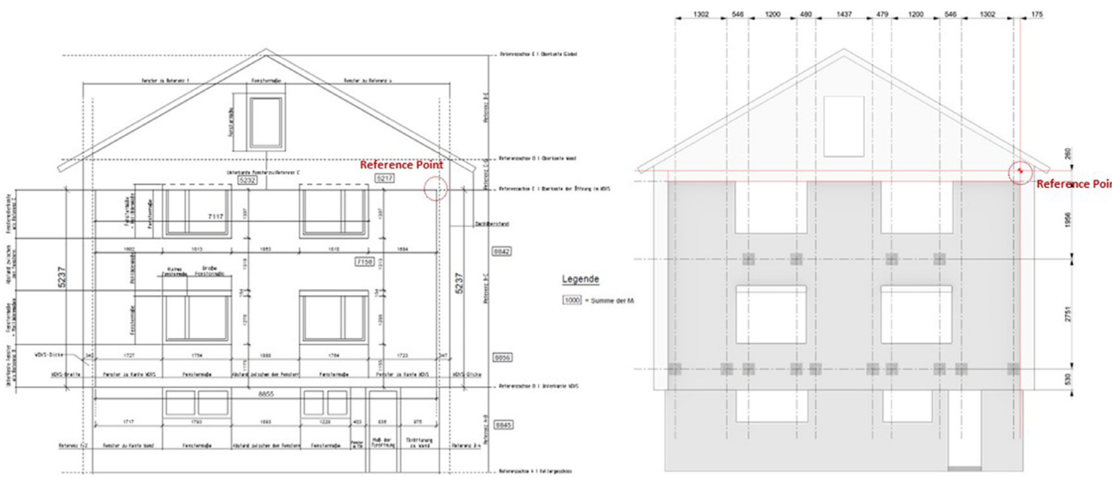

Fig. 28. 2D representation of the measuring integrated in the planning.

Conclusion and outlook

Due to its materiality (ultra-high performance concrete) and its design options (sizes, surface structures, color), the novel TABSOLAR® concept offers new possibilities to use façades as (solar) thermal source for direct usage or as a low-temperature source for heat pumps. Moreover, TABSOLAR® elements can be used inside buildings as heating or cooling elements, also in combination with concrete core activation. TABSOLAR® elements are being developed as “solar-active façade elements”, which means that the collector concept follows the rules of design and construction of façades, not vice versa. This is possible via an interdisciplinary consortium which develops this concept right from the beginning. Based on the new concept, the frameless collector has been newly developed and designed (consideration of collector efficiency factor F', spectrally selective coating, fixing of glazing and absorber, thermal insulation, …). The project considers the overall value chain of the TABSOLAR® concept from an early design phase via the production up to the final installation. Two software tools – an augmented reality (AR) app and a web configurator are being developed. In order to produce TABSOLAR® elements, an innovative production technology has been developed and is now being tested with a small-scale sample plant as a basis for a semi-automated production plant capable of producing large TABSOLAR® elements. A demonstration façade on a renovated two-family house is being planned. The façade will comprise both glazed *TABSOLAR® Premium* elements (solar thermal collectors) and unglazed *TABSOLAR® Design* elements (low-temperature source for heat pumps). The demonstration façade is expected to be installed in spring 2023.

Trademarks

TABSOLAR® and FracTherm® are registered trademarks by Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michael Hermann has patent #EP 1 525 428 with royalties paid to Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V. Michael Hermann has patent #DE 199 35 603 A1 issued to Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.

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