CoolSkin

A Novel Façade Design for Sustainable Solar Cooling by Adsorption

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Abstract

The article investigates the dependencies of façade design and construction in the integration of a sustainable solar-powered cooling system based on closed adsorption. The presented work focuses on the possible design variants of the envelope surface of the façade -integrated adsorber. The principle of adsorption cooling is presented and, based on this, architectural options for façade integration are investigated. This is done both constructively and visually. For each variant, the solar gains are summed up and compared with each other. A functionally designed adsorber, similar to a flat plate collector, serves as a reference and starting point for the modifications. It provides the comparative value for the energy evaluation. The modification is limited to the visible surface of the absorber. The texture of the solar adsorbing sheet was changed and the glazing used was replaced by ETFE cushions and by a novel ETFE vacuum panel. Finally, the solar simulation results were integrated into the higher-level system simulation to evaluate the resulting gain in cooling capacity. The results show that the system could generate more than 100 W per installed square metre of adsorber façade. Furthermore, higher solar gains compared to the reference case can be obtained at particular times of the day due to geometry and material changes. However, the modifications always lead to a reduction of the total cooling power. In conclusion, the simulation results reveal that design flexibility is possible, but currently the studied design variants have a lower cooling capacity compared to the solely functionally designed adsorber.

Keywords

solar cooling, adsorption, façade integrated cooling

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1 INTRODUCTION

1.1 MOTIVATION

The world is getting warmer (Masson-Delmotte et al., 2021). Due to the steady progress of global warming, we are experiencing extreme heat events on Earth with increasing frequency. In many parts of the world, temperatures are reaching levels that are life-threatening for people. In order to slow down the global warming that is responsible for this, the consumption of resources in the building mass will be reduced in the future. In addition, the savings in building mass, and thus CO2, further increases the thermal dynamics of buildings, which in turn leads to faster natural heating of the interior with the risk of over-heating. In the future, we will therefore not be able to operate buildings without active cooling in both existing and new buildings. Current centralized cooling systems have limited retrofit capability due to large pipe cross sections. Decentralized electricity-powered air-conditioning systems cannot be used everywhere due to low heat recovery, noise intensity, and their susceptibility to servicing (Giebeler et al., 2008). In total, air-conditioning systems already consume almost 16 % of final energy consumption in the building sector (about 1885 TWh) in electrical energy in 2020 (IEA, 2021). In order not to further intensify climate change, this cooling energy must be generated in a CO2-neutral way. In this context, a decentralized adsorption cooling system for buildings was developed as part of the Collaborative Research Center 1244 (SFB 1244) at the University of Stuttgart (Germany), which uses the incident solar energy on the building façade. The use of solar energy is not only sustainable, but it is also an attractive option due to the parallelism of cooling capacity and external cooling load (Giebeler et al., 2008). Because of the integration into the façade, the function of solar energy harvesting becomes a design parameter for the architecture.

There are several different solar-based cooling concepts for buildings. These systems are classified according to their energy sources, which are either electrical, as in the case of photovoltaics (PV), or thermal, as in the case of solar collectors. The electrical energy generated by PV is used for cooling by means of compression units or Peltier elements. The former is currently the most common type of solar-powered cooling (Alexopoulos & Kalogirou, 2022). The direct use of thermal energy sources is divided into closed and open systems. Open systems, which can also be used for dehumidification, are based on liquid absorption or solid adsorption. Closed systems work either thermally and mechanically or on the principle of solid adsorption. The respective advantages and disadvantages of the individual systems and their possible use in buildings have been considered in detail in the past (Prieto et al., 2017a). The fact that the systems have not made their way into the built environment is due to several reasons. The main barrier is the performance, aesthetic, and complexity of the existing developments (Prieto et al., 2017b). In the past, the focus of research was mostly on energy optimization, while the integration of solar thermal collectors into the façade was mostly limited to the constructional side. The mounting of existing collectors on the façade rather than integration into the façade is still practiced today. Integration into mullion-transom façades has been realized in a few cases but has not gained widespread acceptance. On the component level, there are several research projects that deal with further integration methods of different systems (Buker & Riffat, 2015), but there is currently no work known that addresses the design and functional integration with respect to the surface of the solar façade. In particular, the time-dependent influence of the surface structure on the solar gains has not been a subject of research in the context of a solar façade until now. Yet new digital manufacturing methods enable the production of individual elements for a specific task.

The aim of this work is to investigate the possibilities of the novel adsorption cooling façade (ACF) system in terms of the visible façade surface from a design point of view excessively reducing the cooling performance. Publications have shown that a purely functional consideration does not necessarily lead to an application in the building context. An important and often neglected aspect is the design integration into the building concept (Prieto et al., 2017b). In this context, the aesthetic of a building is multifactorial and has occupied architects since the time of Vitruvius (1st century BC) until today. The paper "What makes a façade beautiful?" (Prieto & Oldenhave, 2021) sorts the often-mentioned points of façade aesthetics into intrinsic and extrinsic aspects. Intrinsic aspects like colour, proportions, and texture are as important for a "successful façade" as extrinsic aspects like logic, local context, or conceptual clarity. Due to the individual external dependencies of the extrinsic aspects, the paper can only look at the intrinsic aspects.

As detailed in Section 1.2, there are three components of the ACF that must be integrated into the building: Adsorber, Condenser, and Evaporator. This paper only addresses the integration of the solar absorbing adsorber into the façade. Due to the prevalence of element façades in high-rise building construction, this project assumes the integration of the adsorber into a curtain wall element. The element frame and its material will not be discussed further.

1.2 COOLING PRINCIPLE AND PRELIMINARY WORK

The novel façade-integrated closed low-pressure adsorption system for solar cooling was proposed within the SFB1244, which was first mentioned in Böckmann (Böckmann et al., 2022). This adsorption cooling façade (ACF) uses solar radiation as an energy source. It is therefore suitable as a renewal of the façade during building renovations or directly integrated into new buildings. An advantage of the decentralized system is that it could be installed modularly and is resilient to the failure of individual elements. The shifting of cooling generations to the vertical façade reduces the competition for space on the roof surface between HVAC systems, photovoltaics, terrace use or greenspace applications. Vertical thermal energy harvesting has a 30% (Kasper & Heidler, 2011) lower total energy gain than optimally aligned collectors. However, more decisive for the optimal orientation is the time of solar energy input, to harvest solar energy in the morning for cooling the afternoon. In this case a vertical orientation can achieve more solar energy gains compared to a tilted collector, as the solar zenith is low in the morning. Due to the favourable ratio of footprint to square metre of façade and the avoidance of ambient shading, high-rise buildings are most suitable for the proposed adsorption cooling façade (ACF).

The system consists of three main components: adsorber and condenser, both located on or in the façade, and the evaporator, located below the storey ceiling. It runs through two main phases during each day (Fig. 1): the regeneration phase and the cooling phase. During the regeneration phase, the adsorber is heated up by solar irradiation, initiating the desorption of the adsorbed water. As soon as the adsorber is no longer heated due to the repositioning of the sun, the subsequent cooling phase starts. In this phase, the adsorber is connected to the evaporator, continuously re-adsorbs vapour and thereby lowers the vapour pressure inside the evaporator. Consequently, evaporation is induced in the evaporator, resulting in a temperature decrease of the remaining water and thus provides cooling power to regulate the indoor room/building temperature

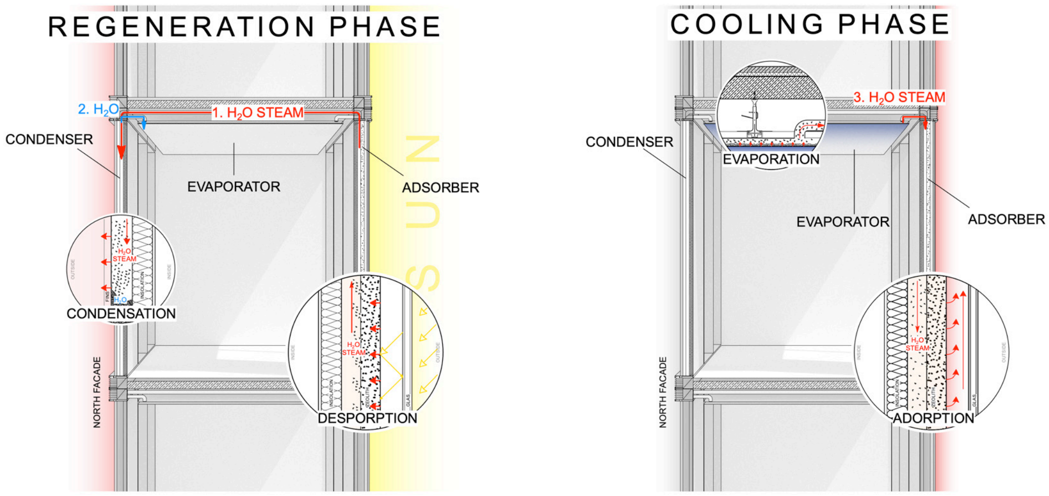


FIG. 1 Integration of the adsorption cooling façade system into one storey of a high-rise building during the regeneration phase (left) and the cooling phase (right)

The simulation of a reference case yields cooling rates of 54 W per installed square metre of adsorber façade, cmp. Figure 2. The cooling power can be maintained for 12 hours, confirming the applicability of the proposed cooling system. However, continuous cooling over the whole day cannot be achieved with only one ACF as the regeneration phase is required. This could be achieved by additional adsorber and condenser elements on the opposite façades of the building, which will be considered in future investigations. The temperatures inside the adsorber reach values of up to 100°C at the end of the regeneration phase, cmp. Figure 2. (Böckmann et al., 2022)

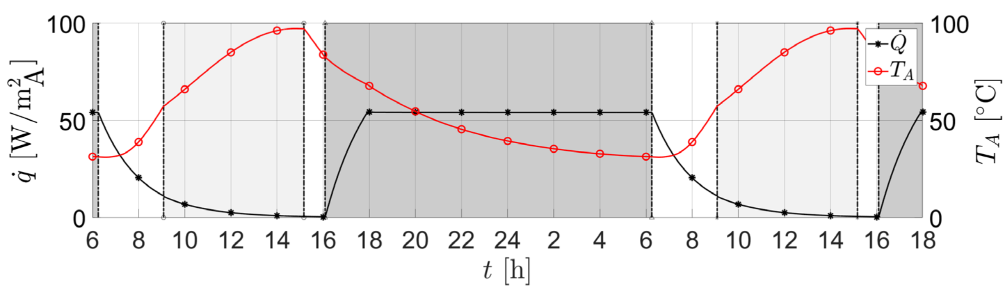


FIG. 2 Evolution of the cooling power (black line) and of the temperature (red line) inside the adsorber over time t. The regeneration phase is shaded light grey and the cooling phase is shaded dark grey.

Additionally, a broad parameter study provided information about possible optimization to increase the cooling rate and cooling capacity. The orientation of the adsorber façade elements, the surface area ratios of the components, and the design of the adsorber were identified as promising optimization parameters. Based on these results, a best-case configuration was identified that revealed cooling rates of up to 150 W per installed square metre of adsorber façade (Böckmann et al., 2022).

2 METHODS

Based on the highest possible energetic gains, a reference collector was developed in a first step, which fulfils the above-mentioned characteristics. This is based on information from the literature for solar collectors and from the functional constraints of the cooling principle. In a second step, the visual and absorptive effects of changes in the different layers of the adsorber are shown by means of two examples. The solar absorptance of the variants was determined simulatively and then each was incorporated into the higher-level component simulation in order to evaluate the effectiveness for the entire ACF.

Rhinoceros 3D software version 7 (Robert McNeel & Associates, Seattle, USA) with the Grasshopper plugin were used to get a three-dimensional parametric model of the Adsorber. The models thereby fulfil the function of a visual assessment and basis for the irradiation simulation. The modelled collectors were 1.5 m by 1.5 m. One square metre centred in it was set as the area to be analysed, to reduce the impact of the frame. The parametric model provides the flexibility for optional optimization steps. The simulation of solar irradiance on the absorbing surface was performed with the plugin Ladybug and with the five-phase method of the Radiance software, used in the environmental analysis plugin Honeybee (Roudsari, 2022) in the Grasshopper graphical programming interface of the Rhinoceros 3D software (Roudsari & Pak, 2013). Ladybug, a tool for analysis of climate data, allows simulation of irradiance on a given surface based on date, location, and geometry. Due to the time-saving simulation method, the subsequent optimization is based on this tool. For a more detailed investigation, the software Radiance was used. The simulation includes the parameter date, location, geometry, colour, reflectance, and transmittance of each specific material to get the hourly effective solar irradiance per square metre. Effects of the frame, back radiation of the environment, and external shading conditions were not considered, as such factors are secondary and must be considered for the individual integration case. The collector efficiency is crucial for the irradiation simulation of the entire system. This depends decisively on the optical efficiency, which relies on the reflectivity and absorptivity of the materials used. The solar absorption coefficient of the highly selective coating is reported to be 96% (Kasper & Heidler, 2011). Since Radiance only calculates the incident radiant energy, all results were multiplied by a factor of 0.96 for the total solar gains. For the absorption sheet, the material was set in Radiance with a specular reflectance of 4%. Both simulations were done with the location as Stuttgart (Germany, 48°44'55.4 "N 9°06'43.2 "E) and the façade orientation of the Collaborative Research Center 1244 demonstrator is approximately south-southeast (SSE) azimuth (-22.5°). The ASHRAE Revised Clear Sky (Tau Model), due to its accuracy for European latitudes, was used as the sky model (Badescu et al., 2013). For th e Ladybug simulation, the direct and diffuse radiation were extracted from this model. 26th August was always assumed for both solar simulations.

The evolutionary optimization tool Galapagos (Rutten, 2013) was used to optimize the geometry of the structures in section 3.3.1 with respect to maximum solar gains. The parameters that could be changed with the optimization tool were the height z and the ratio of x1 to x2, which is described in more detail in Chapter 3.3.1. In addition, the results were transferred to the Rhinoceros 3D environment for visualization. The optimized structure was also again simulated more accurately for its solar irradiance by using Radiance, with the specific material properties of each component. The whole workflow process is depicted in a simplified manner in Figure 3.

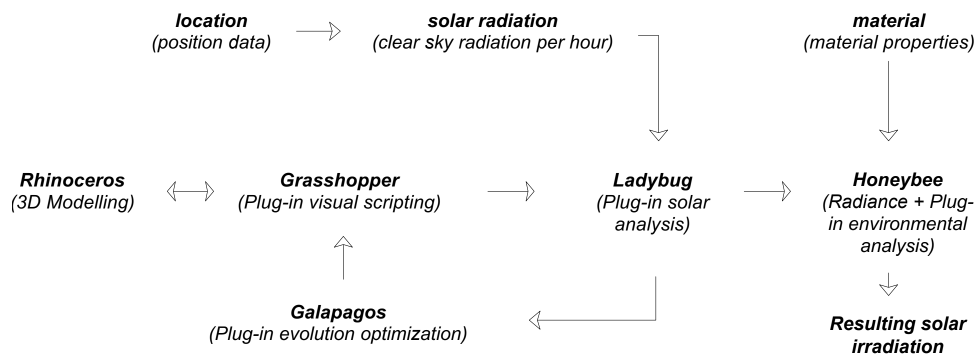


FIG. 3 Workflow diagram for modelling and simulation

The component simulation of the ACF was performed by co-author Boeckmann in (Böckmann et al., 2022) and confirmed the suitability of the system for building applications. Detailed component models were developed for the three main components adsorber, condenser, and evaporator, which are coupled by the vapour flow. The component models describe the internal heat and mass transfer processes as well as the adsorption and condensation/evaporation processes. Simulations of the components were carried out under realistic boundary conditions, applying the evolution of solar irradiation and ambient temperature over time for a summer day in Stuttgart.

3 RESEARCH SET-UP

3.1 BUILDING INTEGRATION PRINCIPLES

On a general level, there are various integration principles for integrating the adsorber element into a façade concept (Fig. 04). Either the system is integrated into the façade level or into the sun protection level. In the case of integration into the façade level, the adsorber element can be located within the insulation layer or in front of it.

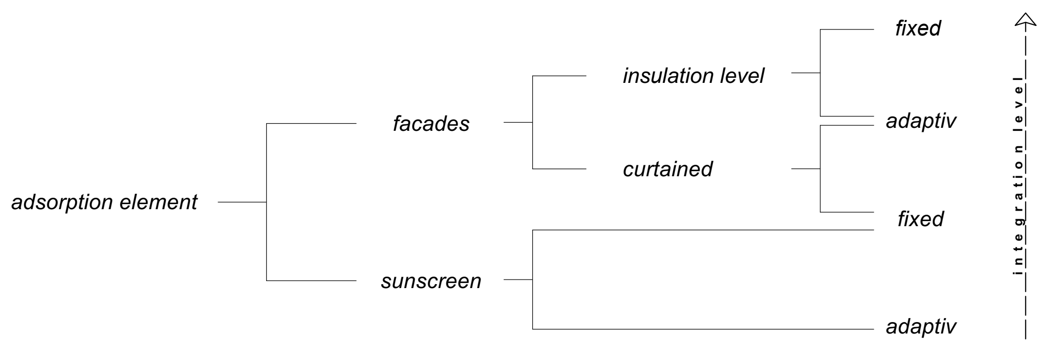
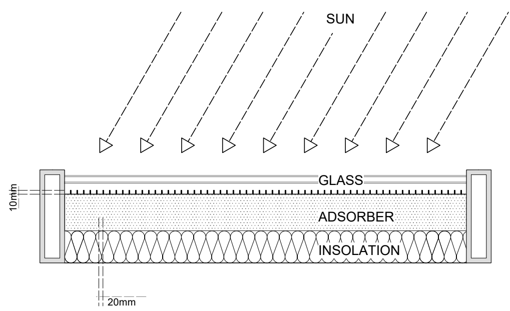


FIG. 4 Integration of an adsorption element

Finally, the various principles are to be considered as both adaptive and fixed elements. With increasing functional integration, the level of integration and also the complexity of the component tend to increase. (Klaiber, Fröhlich, & Vietor, 2019) Regardless of the selected façade system, all principles have in common the design-determining visible surfaces of the components. Since these are the energy harvesting surfaces, they have a large impact on the effectiveness of the overall cooling system. This means that there are functional boundary conditions for the adsorber that must be considered in the design of the adsorber. These are discussed in more detail in Section 3.3.

3.2 REFERENCE ADSORBER DESIGN

The preliminary work (Sect. 1.2) has shown that for the efficient operation of the system, the highest possible temperature difference between the adsorption and desorption phases should be achieved. For this reason, unglazed plastic or stainless-steel absorbers, as they are already installed in façades today, cannot form the basis of our novel collector. Currently, only vacuum tube collectors and vacuum flat plate collectors reach the temperature range of 100°C or more. (Kasper & Heidler, 2011). In contrast to the decisive maximum temperature difference, vacuum collectors are generally only optimized for maximum energy gain. A possibility for rapid heat dissipation to the environment is not provided. Therefore, based on the principle of a conventional flat plate collector, a new type of collector had to be developed, which allows high-temperature differences between regeneration (charging) and cooling (discharging) phases, which is realized through switchable heat release.



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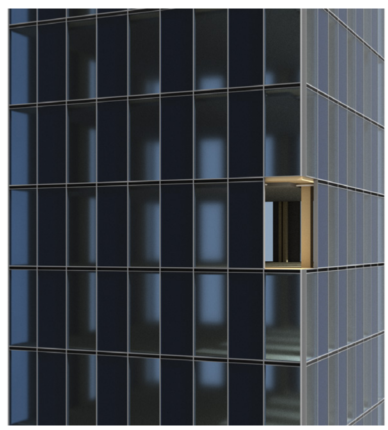

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FIG. 5 [1] Top section view adsorption element with reference design, [2] Example of a façade integration of the reference design

Using the general model of product development (VDI 2221, 2019), a reference design (RD) has been constructed (Fig. 5) as a starting point for the investigations. In contrast to a flat plate collector, double insulating glazing with thermal insulation coating in front of the absorbing surface is applied here. For optimal radiation absorption of > 90% (Kasper & Heidler, 2011), this surface is provided with a highly selective coating (Physical Vapor Deposition (PVD) / Chemical Vapor Deposition (CVD)). The absorbing surface is at the same time part of the vacuum adsorber and responsible for the heat transfer. The resulting air-filled space between the glass and the absorber sheet can be ventilated by means of upper and lower flaps. This vertical convection, which can be activated in the cooling phase, enhances the required heat dissipation and thus facilitates the rapid temperature drop of the adsorber, yielding higher evaporation rates in the evaporator and thus higher cooling power.

The heat release is further enhanced with vertical fins on the absorber sheet to increase the heat emitting surface area. The effectiveness of this approach has been verified by numerical simulations and experimental validation is currently being conducted.

In This new development of a collector, specific to our system, gives the opportunity to consider the design aspects in the functional design and to explore general approaches for the surface design. As starting points, we have identified two layers on the reference adsorber, which contribute significantly influence the appearance (Fig. 6):

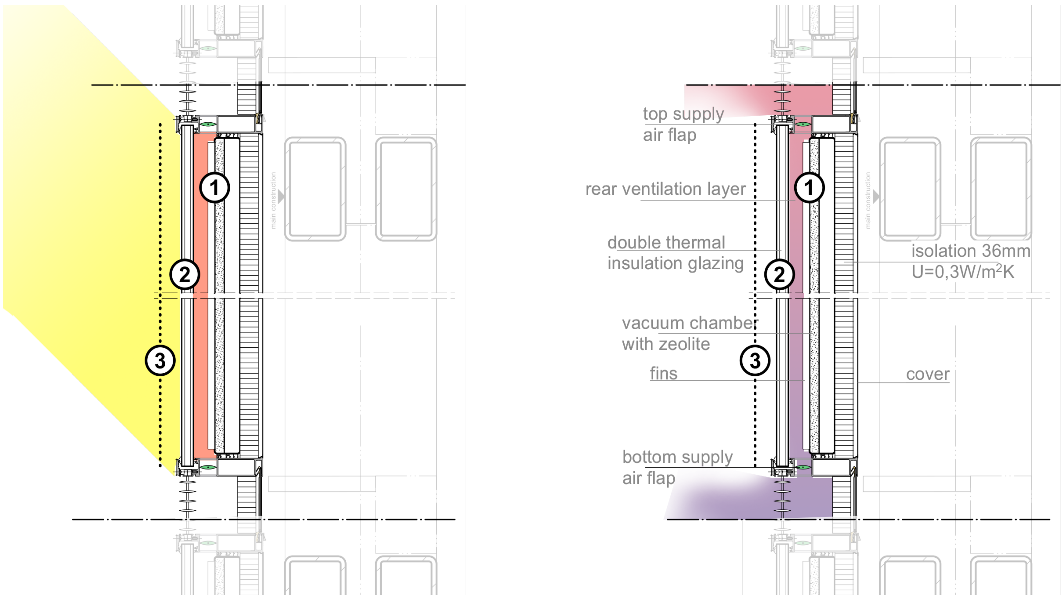

FIG. 6 Section view of the Adsorber element in regeneration phase (left) and cooling phase (right).
Layer **1**,**2** and **3** are discussed below.

Layer **1** is the highly selectively coated (PVD/CVD) aluminium absorber sheet of the vacuum adsorber, which largely determines the colour of the element through the blue/black shimmering coating and is responsible for solar absorption and thermal transfer into the adsorber. In addition, the absorption sheet is responsible for heat dissipation to the interstitial space during the cooling phase and is thus subject to thermal stress. Mechanically, the vacuum of the adsorber acts on the sheet.

Between Layer **1** and Layer **2** is an air gap, which is used for cooling in the cool-down phase. The gap between them is 10mm. Layer **2** is the double insulating glazing. This determines the “materiality” and surface feel of the element through the reflections and transparency. Both aspects, the solar heat gain coefficient and the thermal transmittance (U), are important factors for the efficiency of the collector. At the same time, the surface also represents the outermost weathering layer and, in addition to thermal loads, the surrounding environmental factors also affect this layer.

3.3 MODIFICATIONS AND THEIR EFFECTS ON SOLAR GAINS

The relevant aspects for the aesthetics of a façade surface are colour, material, geometry, proportion, and a continuous design logic (Prieto & Oldenhave, 2021). The colour scheme of the surface is dominated by the highly selective solar energy absorbing PVD/CVD coating. Due to the above-mentioned high efficiency of 90.2% in solar absorption, there is currently no adequate alternative to its bluish-black colour. In comparison, copper has an efficiency of only 4.8% (Kasper & Heidler, 2011). Any change in the colour of the coating can only be achieved by material science and is therefore assumed to be unchangeable. The proportion and a continuous design logic is also not part of this paper, because these aspects are always to be seen in relation to the specific building. The modifications are limited to the geometry and texture of the surfaces and their material. Layers one and two were selected with regard to these aspects and their effects on solar gains were simulated.

3.3.1 Layer 1 - Absorber Sheet Metal

In order to optimize the appearance of this surface visually and functionally, the folding of the aluminium surface is a possible design and efficiency measure with the following positive effects to be expected:

1. The folding structure's slope enables the targeted adjustment of the time of maximum energy input and thus the adjustment of the façade to the system's operating phases (Fig. 7).
2. The larger surface area of the folded structure enables higher heat exchange in the cooling phase compared to the flat plate collector (Fig. 8).
3. A lower material consumption and material thickness due to positive static effects of folding.
4. The folding allows a specific texturing of the total appearance.

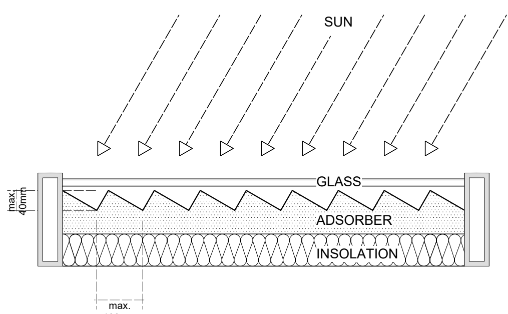

FIG. 7 Top section view of adsorption element with folded sheet

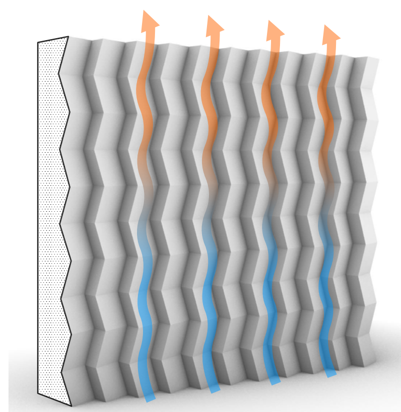

FIG. 8 Thermal air flow through the folded structure

The design of the absorption sheet folding (layer **1**), based on the results of Klett in 2013 (Klett, 2013) on modular isometric origami of folded sandwich structures and the complementary article of adaptive heat transport of such structures Oei et al., 2019). This folding not only increases the stiffness of the element but can be manufactured from a simple two-dimensional aluminium plate. The former saves the necessary material input and the latter the manufacturing effort. The origami structure is designed to allow vertical airflow (Fig. 8) and maximize the absorbing surface in the defined period (Fig. 7).

The research project "SolarShell" at the University of Leipzig has shown the positive effects that parametric convolution can have on the energy income (Hülsmeier et al., 2017) and, in contrast to our work, investigated the total yield of PV cells. However, due to their structure, the simulations carried out indicate that the thermal solar gain can also be increased by an adjusted alignment. In our case, the maximization of the solar area was performed with the simulation of the solar irradiation with the plug-in Ladybug and optimized using Galapagos. A façade orientation SSE was assumed as an optimization parameter for the Stuttgart (Germany) site and the period from 05:00h to 12:00h for the whole month of August. A width (y) and depth (x) of 100mm and a maximum height (z) of 40mm were defined as the optimization framework (Fig. 9). The initial structure for the convolution was assumed to be $y_1=y_2$ and $x_1=x_2$. For the optimized structure, the ratio x_1 to x_2 was adjusted. In the optimized state, the structure has approx. 50% more surface area than a flat sheet with the same base area. This number can be increased by reducing the width/depth or increasing the height.

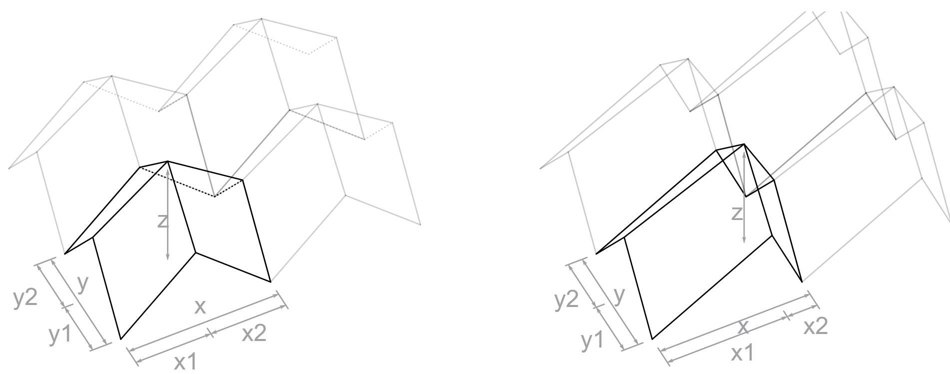

FIG. 9 Optimization method for the isometric folding structure, design/approach based on (Klett, 2013)

3.3.2 Layer 2 – Glass Substitution with an ETFE-Vacuum-Panel (EVP)

Another possibility for design and functional manipulation is the replacement of the double insulating glass pane. Glass is a relatively heavy material, which is in contradiction to the overall goal to reduce resource consumption in the building sector. As a result, especially in the renovation of high-rise buildings, the weight of the façade means that the supporting structure has to be improved. Due to the thermal load on the inside, most highly transparent plastics, such as PE, PP, and PET are not suitable. With a melting point of about 280°C and transmittance of approx. 91%, ETFE (ethylene-tetrafluoroethylene) is very well suited to the class of plastics in the use of a collector. Due to the high e-modulus, resistance to environmental influences and the "lotus" effect of the surface, ETFE has been used in the form of cushions in façades for several years. It could also include, with a 2-layer structure, into the adsorber element (Fig. 10).

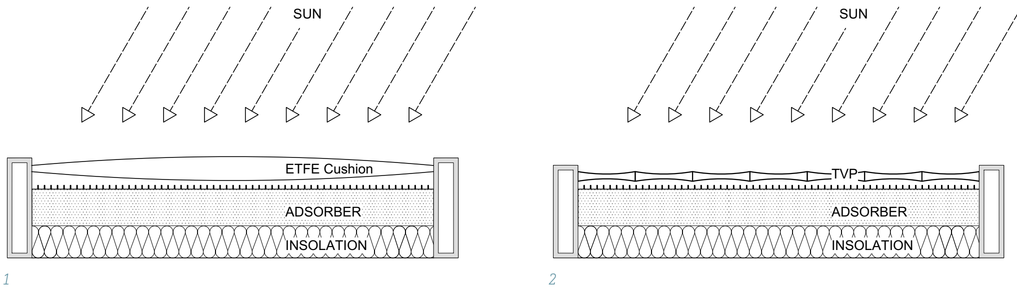

FIG. 10 Top section of the adsorber element with ETFE cushion (left) and transparent vacuum panel (right)

In order to achieve the U-value of double insulating glazing of approx. 1.1W/(m2K), cushion constructions with 3 layers of ETFE are currently used. Since the transmittance decreases with each layer and a pillow construction requires more space volume in the collector, a completely new type of panel was developed with a 2-layer vacuum design (Fig. 10). To ensure the distance between the foils, a supporting structure in between is also needed. This transparent ETFE Vacuum Panel (EVP) thus serves as a design element. By colouring or choosing the material of the internal structure, the appearance can change depending on the angle. This is one of the few possible colour influences, and more complex representations are also possible as a result.
The span (Cd) of the supporting structure depends on the tensile strength (T) of the ETFE foil, the pressure outside (P(i)) the height of the structure (h) and the minimum distance (Az) between the two foils (Fig. 11). For ETFE the tensile strength is T=30N/mm, h is set to 30mm and Az is fixed at 10mm. These values result in a maximum span of approx. 218 mm. In the structures examined, this was limited to 200mm.

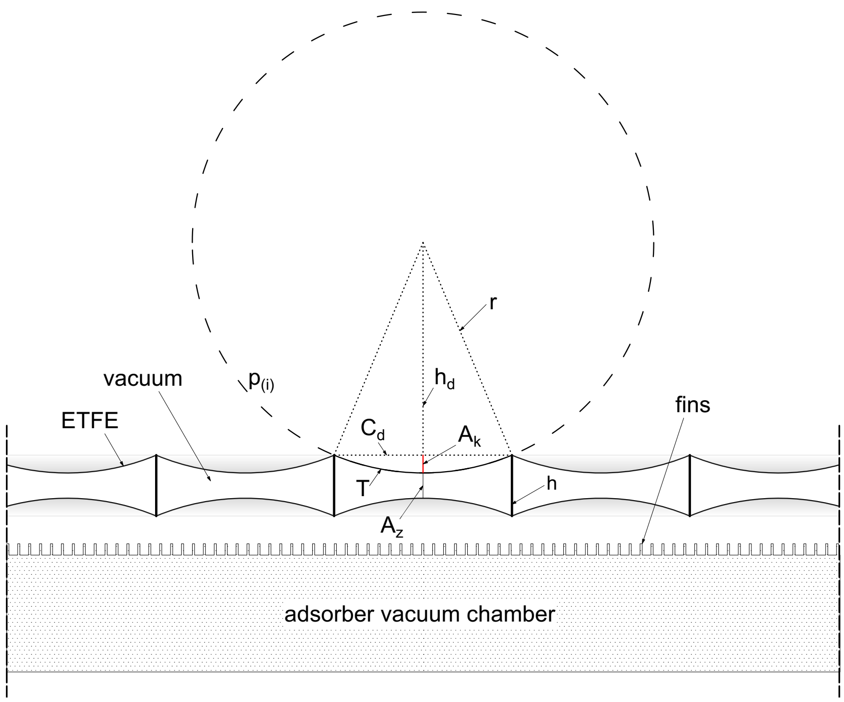

FIG. 11 Calculation sketch for the grid size

Four structures were investigated which could be used as a support structure. Horizontal and vertical lamellas, a grid structure, a hexagon, and a Voronoi structure (Fig. 12). The 2D footprints of the structure are between 0.083% and 0.09% of the total surface. These structures are to be considered exemplary and planners have the freedom to develop their own. The results of the structures obtained here can be used as a reference for geometric principles of new structures.

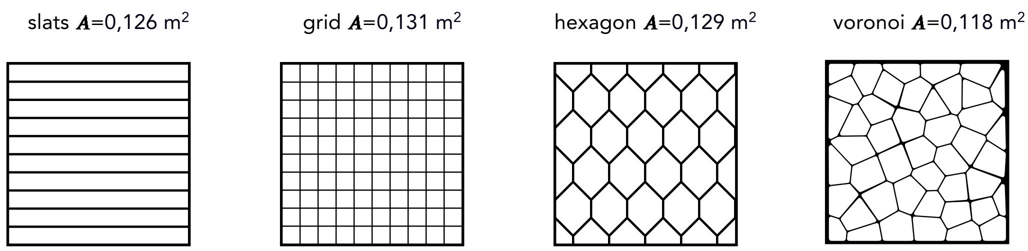

FIG. 12 Simulative studied pattern of support structure

4 RESULTS AND DISCUSSION

4.1 SIMULATION 1 – SOLAR GAINS OF THE REFERENCE DESIGN

In order to classify the absorbed solar energy for the reference design, the solar irradiation of a surface and a surface with solar glass, similar to the structure of a flat collector, were simulated. For the whole of August 26th, the energy simulation in Radiance shows with a south-southeast orientation a total irradiation for a vertical surface of 5108 Wh/m², for a flat plate collector with 4385 W/m², for the reference design with solar glazing (RD - transmission 91%) of 4674 W/m² and for the reference design with double insulating glazing (RD -transmission 83%) of 4214 W/m² (Fig. 13).

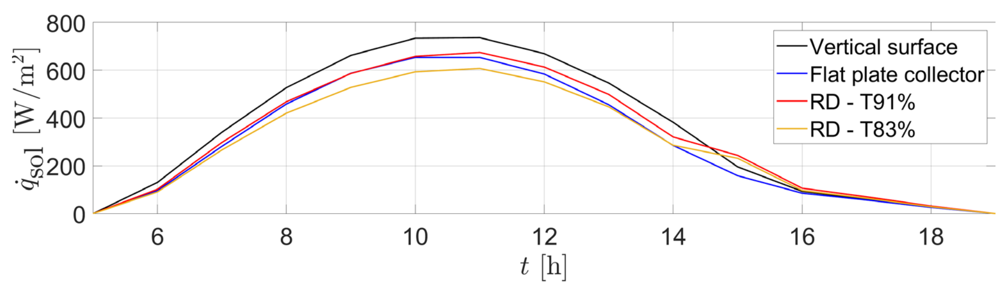

FIG. 13 Solar gains of a vertical surface, flat plate collector, reference design with solarglass T91% and reference design with double glazing T83%

This means that the irradiation on the 'RD - T91%' is 91.5% and on 'RD T-83%' it is 82.5% from the total irradiation on a vertical surface. As expected, the result correlates with the transmission coefficient of the two different glasses. Comparing the flat plate collector with the RD-T91%, the solar gains are almost identical except for the period between 2pm - 4pm. This slightly higher gain of the RD-T91% is due to the marginally better alignment by the fins on the surface of the RD. It can be concluded that the fins on the adsorber surface have a small influence on the optical energy gain, however a much better heat transfer in the cooling phase can be assumed because of the double surface.

By making a comparison between the RD with single-layer solar glazing and the RD with double-layer insulating glazing, the latter is 10% worse overall. In order to compare the two, the thermal losses must be considered in addition to the optical efficiency. These are assumed to be the same except for the glazing. The useful heat output (q_N) can be calculated by the difference between the useful irradiation (E_N) and the thermal losses (q_V) (Kasper & Heidler, 2011).

The thermal losses depend on the temperature difference (ΔT) between the absorber and outside air. If one assumes this very conservatively with ΔT 60° Kelvin at 12 am, a U-value for the solar glass of 5.8 W/m²*K and for the insulating glazing of 1.1W/m²*K (*Glaströsch*, 2022), the following result is obtained. The RD – T91% has a useful heat output at 12 am of 613 W/m² – 5.8 W/m²*60 = 265 W/m² and the RD – T83% has a useful output of 551 W/m² – 1.1W/m²*60 = 491 W/m². The real power is additionally dependent on the heat losses at the frame and backside. The single-layer solar glazing has a very high heat transfer co-efficiency and the efficiency of the collector decreases due to heat losses through the glass. In addition, condensation on the inside of the single-layer glazing is to be expected, which also reduces the solar gain.

$$q_N = E_N - q_V$$

FIG. 14 Useful heat output to irradiation and thermal losses

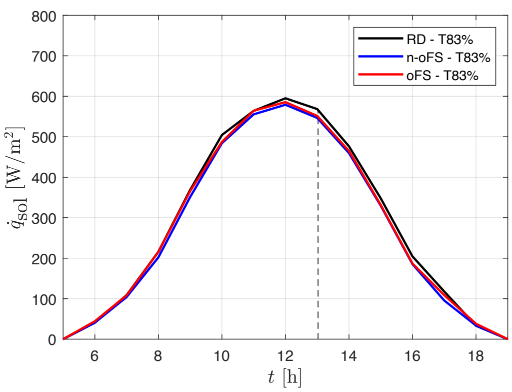

FIG. 15 Comparison RD-T83% with n-oFS and oFS aligned to south

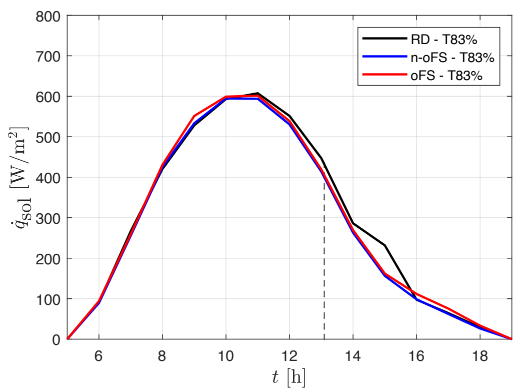

FIG. 16 Comparison RD-T83% with n-oFS and oFS aligned to south-southeast

4.3 SIMULATION 2 – SOLAR GAINS OF THE FOLDING ADSORPTION SHEET

The folds on Layer **1** were simulated for three directions, east (E), south-southeast (SSE) and south (S). In each case, the reference design with double insulation glazing (RD-T83%) was compared with the non-optimized folded sheet (n-oFS) and a folding sheet optimized for orientation (oFS). The period considered was always the full day of August 26th. Looking to the south orientated simulation (Fig. 15), the results are 4146 Wh/m² for the RD-T83%, 3967 Wh/m² for the n-oFS and 4053 Wh/m² for the oFS. Overall, the values are very close to each other and improvement in energy input due to surface optimization is hardly evident. The simulation of the SSE orientated collectors (Fig. 16) resulted in a total solar gain of 4214 Wh/m² for the RD-T83%, 4043 Wh/m² for the n-oFS and 4146 Wh/m² for the oFS. The overall values are also very close to each other, but the optimized surface has a higher gain in the time between 5 am and 10 am.This promotes faster system dynamics and can thus provide cooling power sooner. A time shift was possible by the oFS. The results of the simulation with east orientation (Fig. 17) have a total solar irradiance of 3511 W/m² for the RD-T83%, 3288 W/m² for the n-oFS and 3641 W/m² for the oFS. The results show a significantly larger solar gain from the optimized convolution to n-oFS with 10% and to RD with 4%.

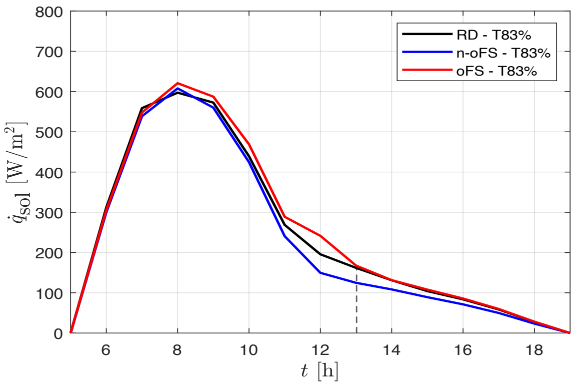

FIG. 17 Comparison RD-T83% with n-oFS and oFS aligned to east

It can be seen that the further the façade is from the optimal orientation to the sun in the south during the desired time period, the greater the additional gain between the non-optimized and optimized folding. In addition, the results show that the optimized folding can shift the solar gain slightly more into the morning hours. It is worthy of discussion whether such a small increase justifies the effort of an individual adjustment of the convolution for alignment and time. But the positive properties from 3.3.1 are also given for an unoptimized convolution.

4.4 SIMULATION 3 - SOLAR GAINS WHEN USING ETFE

The aim of simulation 3 was to investigate the influence of the material ETFE and an internal support structure on Layer **2** (Fig. 18). As with the investigations before, a façade orientation to SSE on August 26th is considered as an example. This shows the values 4214 Wh/m² for the RD, 4121 Wh/m² for an ETFE cushion, 2959 Wh/m² for the EVP with a grid support structure, 2880 Wh/m² for EVP with a hexagon support structure and 3091 Wh/m² for the EVP with Voronoi support structure.

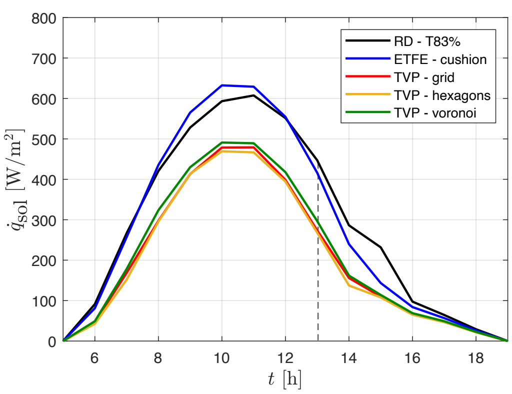

FIG. 18 Comparison RD-T83% with ETFE cushion and EVP with grid/ hexagons/ Voronoi structure aligned to SSE

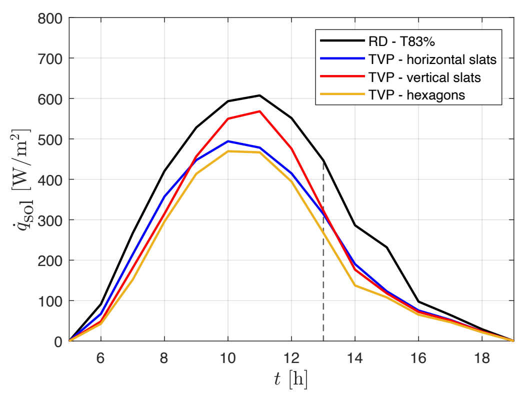

FIG. 19 Comparison RD-T83% with EVP with horizontal and vertical slats and with a hexagon structure aligned to SSE

Using an ETFE cushion, the solar radiation between 5 am and 1 pm is 3% higher than with the RD-T83%. At first glance, this seems to support the use of an ETFE cushion as an outer layer, but, as in Section 4.1, thermal losses must be taken into account. An ETFE cushion has a U-value of approx. 3W/m^{2}K (Knippers et al., 2010) compared to a value of 1.1W/m^{2}K for double glazing. With this in mind, the EVP, with its likely better U-value, is the better choice despite the poorer solar gains. The different results of the structures show a dependence on the solar gain and the geometry. This dependence is further explored in Fig. 19 with vertical and horizontal slats. In particular, the horizontal structures have a 26% negative impact on solar gains until 1 pm. There is still a high degree of geometric optimization of the support structure webs through design minimization, a reflective coating and also tilts adapted to the position of the sun. Further simulative and experimental research must clarify these issues.

4.5 VISUAL IMPACT

The visual impact of a building element is always related to the entire building and its surroundings. Thus, an evaluation is only possible individually according to integration criteria. Based on the integration studies of solar systems (Munari Probst & Roecker, 2019), we have established the following criteria: colour appearance, texture, depth effect, homogeneity. Depending on the façade context, other criteria such as gloss level, roughness and mechanical load-bearing capacity may be of interest. Further research is needed to clarify the influence of these points, as they are more material-specific properties than structural ones. The investigated manipulations were sorted into an evaluation matrix (Table 1) and rated as follows: not influenceable/ low (-), slightly influenceable / medium (o), and strongly influenceable/ high (+).

TABLE 1 **Evaluation matrix of the visual criteria with evaluation of the solar gain.**

	colour appearance	texture	depth effect	homogeneity (existing)	solar gain
reference adsorber	-	-	-	+	+
Folded sheet	-	o	-/o	+	+
ETFE cushion	-	-	o	+	-
ETFE vac. panel	O	+	+	o	-

It turns out that planners can individualize the ETFE vacuum panel the most. However, the functional values are poor. The folded sheet is the most balanced. For a practical application, further investigations must extend this evaluation matrix and expand it to a catalogue with the most diverse variants. Likewise, further criteria must be added and the presented criteria must be further differentiated. It would be important to have a direct indication of the solar gains depending on the orientation of the building.

4.6 SYSTEM ANALYSIS

Finally, the effect of the different approaches on the cooling rates, achievable with the proposed system, is investigated. For this reason, the different solar irradiation curves, determined in the previous sections, are applied to the model of the system presented in Section 1.2. The focus of the simulation studies is on the cooling power overtime during the cooling phase in the afternoon and the results are shown in Fig.20.

It is found that the highest cooling rates can be achieved with the reference design. The folding of the absorber sheet slightly increases the solar irradiation, but decreases the overall surface, compared to the reference design with the additional fins. This leads to a decreased heat release to the ambient in the cooling phase, which results in a lower cooling rate. Replacing the double insulation thermal glazing with a 2-layer ETFE cushion results in higher thermal losses in the regeneration phase and thus in a lower adsorber temperature. This limits the cooling rate, which is highly influenced by the heat release of the adsorber. The EVP has a comparable insulation effect as the glazing, but this cannot compensate for the much lower solar irradiation. Consequently, the adsorber temperatures and thus the cooling power is reduced.

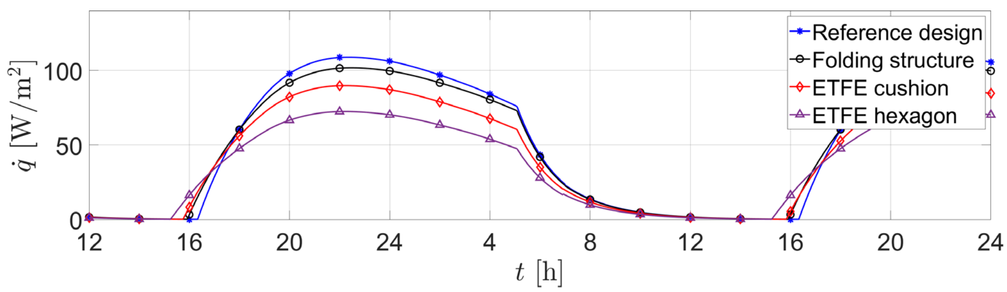

FIG. 20 Cooling power of the investigated reference design with double glazing T83%, folding structure, ETFE cushion and a ETFE hexagon structure

In order to evaluate the design possibilities of the absorber, the variants must meet the necessary cooling power per square metre footprint. This cooling power must be calculated individually for each building and depends strongly on the location (building zone), geometry, construction method, use (internal heat sources), and the control concept (DIN V 18599-2, 2018). Nevertheless, in order to make an initial assessment and evaluation of the various changes, the example of the cooling load calculations of VDI 2078 (VDI 2078, 2015) were looked at more closely and the generally used rough formula of the cooling power calculation was taken (Hanse Handels Haus GmbH, 2021). Thereby, a rough cooling power of 60W/m2 for residential buildings and up to approx. 100W/m2 for commercial buildings is given. Taking these rough values as a basis, replacing the glazing with an ETFE element is possible, but does not achieve the cooling performance for all usage scenarios. The EVP in particular must be viewed critically, as it only provides more than 60W/m2 of cooling capacity over a very short period of time. Since this variant offers the greatest design potential for planners due to the additional support structures, the existing optimization potential must be further explored. The ETFE cushions have the disadvantage that the existing pressure must be maintained. This requires additional energy and technology and is only worthwhile in large-scale use. Manipulation by folding the absorption sheet has the greatest potential in terms of energy, but the optical effect is limited due to localization behind the glass pane.

5 CONCLUSION

In summary, the study has shown that geometric and material surface manipulation of the ACF adsorber is always associated with a loss of cooling performance. Thus, although design manipulation of the surface is possible, it is always subject to functional constraints. Thus, manipulation of the colour was generally ruled out because the highly selective coating only allows adsorber temperatures above 100°C and was assumed to be unalterable. Any design must take into account both solar irradiance and the fastest possible cooling of the adsorber before the cooling phase. From the present research, trends for surface design parameters can be deduced, but need to be confirmed by further studies. The tendencies are that for layer 1 the light transmission of the material is crucial and any additional structure that can be used for shaping reduces it by shading. For layer 2, the study shows that the surface geometry can have a positive influence on solar energy gain. Unfavourable façade orientations can thus be compensated for to a certain degree. In conclusion, the design of the energy harvesting surfaces is always a balancing act between function and design.

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