

Article

Dynamic Optimisation of Façade-Integrated Solar Cooling Elements: Adsorption Cooling Versus Photovoltaic Scenarios

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Abstract

Façade-integrated solar cooling technologies enable the utilisation of façade surface potential and the provision of resilient cooling. This work compares three solar cooling scenarios, positioning a solar cooling element in the west and east façades. The 2ACE scenario is based on a compact adsorption cooling concept, while the 2PV scenario directly drives a compression chiller with photovoltaic elements, and 2PVB incorporates an additional battery. All Modelica system models are implemented in Modelon Impact and operated using dynamic optimisation for the hottest day of the year. Results indicate that the 2ACE scenario, utilising the adsorbent Silica Gel SG123, achieves near to double the self-sufficiency compared to Zeolite 13X. No clear optimal area balance between west and east elements is apparent. The 2PV scenario only surpasses the 2ACE scenario's self-sufficiency with increased total element area, whereas 2PVB enables a drastic increase and complete self-sufficiency. This highlights the limitation of the adsorption cooling scenario due to its inability to compensate for ventilation's electrical energy consumption. However, photovoltaic scenarios are heavily reliant on the assumed energy efficiency ratio. Additionally, slender buildings with a low AV ratio require less façade area to achieve the same self-sufficiency level as wider buildings.

Keywords: Modelica; Modelon Impact; dynamic optimisation; solar cooling; adsorption; façade integration; silica gel; zeolite; compression cooling; photovoltaic; battery

1. Introduction

1.1. Motivation

The buildings sector accounts for 37 % of global annual CO₂ emissions, with 9 % only attributable to the provision of cooling energy [1]. Relative to 2020 levels, this demand for cooling energy is projected to increase by between 29 % and 157 % by 2050 (Figure 33, [1]). “Higher energy consumption for cooling is strongly associated with a very significant increase of the peak electricity demand that obliges utilities to build additional power plants to satisfy the extra needs for electricity” [2]. One recommended policy action is improving the efficiency of compression chiller and alternative cooling technologies [2]. Furthermore, the study [3] identified heatwaves and power outages as major disruptions to be addressed by resilient cooling technologies.

Solar cooling technologies could offer a potential solution, as they operate either partially or entirely independent of an external power supply. Given that the façade area significantly exceeds that of the roof, particularly in high-rise buildings, façade-integrated solar cooling solutions present a viable approach. In this context, the study [4]



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systematically compares five solar cooling technologies in terms of technical feasibility, physical integration, durability and maintenance, and performance, as well as aesthetics and availability. These include thermoelectric, adsorption, absorption, and solid and liquid desiccant systems [4]. Regarding the technical feasibility of the investigated small-scale prototypes, those operating on the thermoelectric cooling concept were found to be the most advanced. Moreover, they demonstrate “clear advantages, being based on simple direct contact between components, besides simple electrical connections to the photovoltaic array for energy input.” [4]. However, they are effectively ruled out due to their low cooling capacity, which currently falls short of the levels required for decentralised cooling [4]. For such applications, technologies based on absorption or adsorption processes are more suitable. Furthermore, these systems possess an intrinsic cooling energy storage capacity, thereby enabling the decoupling of solar energy input from cooling production. However, such systems are currently employed commercially almost exclusively in large-scale, centralised cooling applications. Unlike absorption liquids, adsorption materials exhibit neither toxic nor corrosive properties. In addition, they ensure low-noise operation and significantly reduced maintenance requirements, as they contain no moving parts [4].

1.2. Literature Review on Façade-Integrated Adsorption Cooling

In studies [5,6], experts were consulted regarding the key technical and product-related enabling factors of façade-integrated solar cooling concepts. The primary concerns raised related to the working principle, size, technological maturity, assembly, and applicability to various environmental conditions. In this context, “the importance of having a proper system operation during the use phase in order to avoid various issues related to the inefficient use of the technology” (p. 12, [5]) and “the lack of tools for the prediction of long term performance, and operational limitations of current available systems” (p. 104, [6]) are highlighted. The main research objectives for façade-integrated adsorption cooling systems involve the investigation of compact, modular systems that facilitate plug-and-play assembly. In addition to appealing aesthetics, the system should be simple, adaptable, and applicable to diverse locations and installation contexts [5,6].

1.2.1. Compact, Modular Design

The study [7] proposes a unit comprising multiple solar collector tubes. Each tube consists of an absorber section and a combined condenser/evaporator section. An absorption process is utilised in this configuration. Furthermore, a ventilation concept is integrated into the unit. The device is described as compact and modular.

The studies [8–10] are based on a concept in which the solar collector is integrated into the façade, whilst the heat transfer fluid is stored and drives a continuous two-bed adsorption process. The location where the two-bed adsorption chiller is installed is not specified.

Since 2021, a research group within the Collaborative Research Centre CRC1244, of which the authors of this study are members, has been engaged in the development of a façade-integrated adsorption cooling concept (1ACE), cf. Figure 1a. This was first presented in studies [11,12]. In this design, the adsorber and condenser are allocated to separate façade elements, while the evaporator is integrated into the room as suspended ceiling cooling. In study [13], the concept (1ACE) is extended to include a second adsorber element (2A1CE) on the opposite side of the façade, cf. Figure 1b. However, these concepts do not meet the requirements for modular, compact, and “plug-and-play” installation, as the adsorption components are distributed across individual façade elements and require interconnection via vacuum hoses.

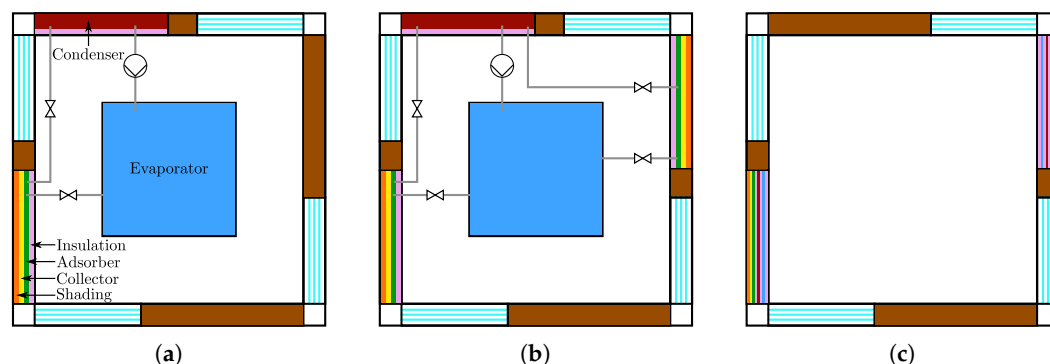


Figure 1. Previously investigated façade-integrated adsorption cooling concepts (1ACE and 2A1CE) and the novel compact concept 2ACE. The modular 2ACE concept has internal valves and a pump but no vacuum hoses throughout the room. The colour code applies consistently. (a) 1ACE. (b) 2A1CE. (c) 2ACE.

1.2.2. System Modelling

The studies [8–10] employ a steady-state model for the efficiency of adsorption cooling, cf. Equation (2) [8]. This does not constitute a detailed model of adsorption kinetics (working pair), heat transfer resistances within the components, or vapour–liquid equilibria. Such detailed models are termed lumped parameter models and are necessary to predict the real behaviour of adsorption cooling systems. Alongside equilibrium models and detailed distributed parameter models, lumped parameter models are regarded as a compromise between component-level detail, system-level validity, and computational efficiency [14]. To this end, the study [15] presents a dedicated open-source Modelica library and its experimental validation.

In previous work within the Collaborative Research Centre CRC1244, the lumped-parameter approach has been consistently applied, predominantly focusing on the working pair Zeolite 13X–water. Additionally, the studies [13,16,17] investigate alternative adsorption pairs. In this context, it was found that silica gels enable a higher cooling capacity for the present application than Zeolite 13X.

To accelerate the cooling of the adsorber and prevent solar irradiation, collector shading was added as an additional control variable in the studies [13,18].

Furthermore, previous works differ in the modelling of the building. A detailed thermal resistance capacitance building model was incorporated into the system dynamics only in the studies [12,13,18,19].

1.2.3. Control Strategies

To operate the overall system, comprising the room model, the ventilation, and the adsorption cooling concept, a control strategy is required. This strategy should account for the geographic location, the orientation of the façade elements, and other static system parameters whilst comparatively exploiting potentials.

In the studies [8–10], no operational strategy for the adsorption cooling process is presented. The studies [14,20,21] consider the control of centralised two-bed adsorption chillers. In a two-bed adsorber, both individual beds are operated in a complementary manner via an arrangement of three-way valves. Their control is achieved by dividing the operating time into a cycle consisting of four operating phases, each with predefined discrete settings for the system inputs. These include the pre-heating, desorption, pre-cooling, and adsorption phases (Figure 2.1, [14]). The durations of these operating phases constitute degrees of freedom. These can be reduced from four to a single degree of freedom

through the application of flap valves and the complementary operation of two adsorber beds [20].

The work conducted within the Collaborative Research Centre CRC1244 investigates a façade-integrated single-bed adsorber. In contrast to conventional two-bed adsorbers, the high temperature level is not provided continuously. Instead, it is dependent on incident radiation and is thus strongly influenced by the orientation of the element. All preliminary studies within the CRC1244 research group employ operational strategies that similarly divide the simulation time into the four aforementioned operating phases. Switching between operating phases is predominantly governed by heuristics, with the strategy described in study [11] being the most commonly applied. In contrast, the study [12] determined the switching times based on the solution of an optimisation problem. The study [19] implemented a reinforcement learning control approach. However, previous work has not yet explored the potential of dynamic optimisation of façade-integrated adsorption cooling elements without the constraint of predefined operating phases.

1.3. Research Gaps and Contributions

The present literature review reveals a significant research gap regarding a compact and modular adsorption cooling element. Consequently, this study introduces a novel concept (2ACE), cf. Figure 1c. In contrast to the concept comprising two adsorbers and a single condenser and evaporator (2A1CE) discussed in study [13], this work integrates one modular element, containing all three components, into both the west and east façades. This constitutes the first research contribution.

However, it remains unclear how large both elements should be and whether there exists an optimal capacity distribution or area balance between the west and east orientations. This is investigated in greater depth in this study. This constitutes the second research contribution.

Additionally, the adsorbent Zeolite 13X is compared against Silica Gel SG123. This is the third contribution as it was not yet investigated for this concept.

Moreover, previous studies within the Collaborative Research Centre CRC1244 have not yet examined a photovoltaic-powered solar cooling element. This study compares the novel adsorption cooling concept (2ACE) with a scenario providing off-grid cooling via two façade-integrated photovoltaic elements and a compression chiller, the concept 2PV. Furthermore, the addition of a battery is investigated in the scenario 2PVB. The comparison of these two scenarios with the adsorption cooling scenario 2ACE constitutes the fourth research contribution.

For this purpose, the self-sufficiency level is defined. It differs from the solar fraction presented in the study (Equation (1), [8]) in that it is not the cooling energy provided by the solar cooling element that is compared to the reference scenario but rather the electrical energy consumption. This makes it possible to compare electrically and solar thermally powered cooling concepts.

Furthermore, the relationship between the building types under consideration, specifically the slenderness of a structure as represented by the AV ratio, and the degree of self-sufficiency has not been clarified by previous studies. This constitutes an additional research contribution of the present study.

The primary contribution of this work, however, is the application of dynamic optimisation for the control of the façade-integrated solar cooling scenarios. Solving dynamic optimisation problems represents the first stage in the development of economic model predictive control concepts. In contrast to previous operational strategies, dynamic optimisation offers significantly increased flexibility, as it does not dictate fixed operating phases.

To achieve this, a system model is formulated that meets the associated requirement for twice continuous differentiability.

1.4. Hypotheses

The following hypotheses are examined in this study:

- H1: Given an identical total area of both elements, the new concept (2ACE) enables a higher degree of self-sufficiency than the concept (1ACE).
- H2: The adsorbent Silica Gel SG123 is better suited for the novel 2ACE façade-integrated adsorption cooling concept than the adsorbent Zeolite 13X.
- H3: Replacing the adsorption cooling elements with photovoltaic elements results in a comparable self-sufficiency level.
- H4: Adding a battery to the photovoltaic scenario increases the self-sufficiency level.
- H5: Slender building types with a high AV ratio can be supplied with solar cooling more self-sufficiently than broad building types with a low AV ratio.

1.5. Section Description

This work is structured as follows:

- Section 2 presents all underlying methods. In addition to the location and the day of investigation, the framework for solving the dynamic optimisation problems and the computational server utilised are described. Subsequently, the system models and dynamic optimisation problems for all scenarios are introduced. These include all states, inputs, and constraints.
- Section 3 presents the results of the parameter variations. These are intended to systematically investigate the influence of the adsorbent material and central system parameters on the degree of grid-neutral cooling supply.
- Section 4 discusses the results and examines the presented hypotheses. Furthermore, limitations and future work are discussed.
- Section 5 summarises the key findings and discussion points.

2. Material and Methods

In Figure 2 the overall models of the reference, adsorption cooling, and photovoltaic scenarios are shown. The overall models of the three investigated solar cooling scenarios extend the model of the reference scenario. The sub-models employed are presented in the subsequent subsections.

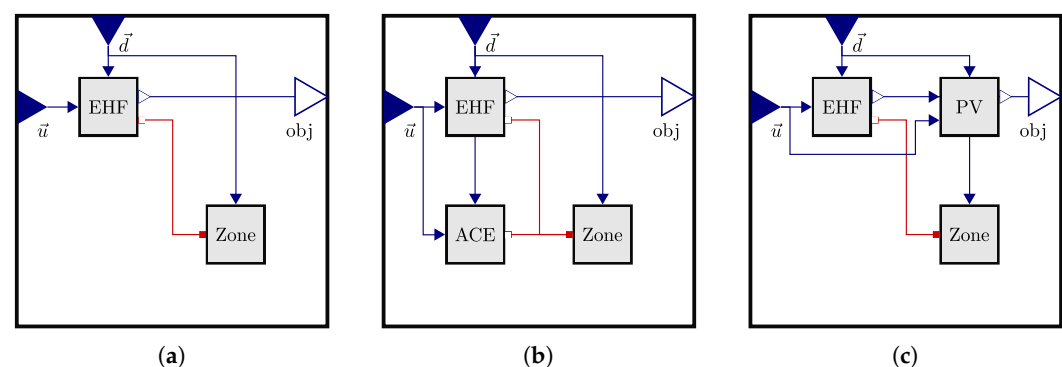


Figure 2. Block diagrams of the scenarios under investigation. The blocks describe the models of the zone (Zone), external heat fluxes (EHF), two adsorption cooling elements (ACE), and two photovoltaic elements (PV). (a) Reference scenario. (b) 2ACE scenario. (c) 2PV or 2PVB scenario.

Typical meteorological weather data was generated for the location of the adaptive high-rise D1244 [22] (N 48.749°, E 9.112°) using the Meteonorm (v8.2.0) software. Only

the hottest day of the year, 25th July, is simulated. The Modelica editor “Modelon Impact” was used for modelling. To solve the dynamic optimisation problems, the open-source nonlinear solver “ipopt” [23] is employed, which utilises the proprietary linear solver “ma57”. A prediction horizon of $t_1 = 24$ h is applied for all scenarios. The time step is initially chosen as $\Delta t = 15$ min for all scenarios but is increased to $\Delta t = 60$ min for the adsorption cooling scenario during the investigations. The complete Modelica code of the system model is openly available. The open-source libraries Buildings [24] and SorpLib (v1) [15] have been used.

The calculations are performed on a Captiva R72-656 Linux server with an AMD Ryzen 9 7900X CPU and 64 GB RAM. The calculations of all data points of the parameter variations on the Linux server are controlled via the Python library `modelon.impact.client` (v4.10.0).

2.1. Reference Scenario

The system diagram of the reference scenario is shown in Figure 2a. It consists of a model for the building envelope (Zone) and the external heat fluxes (EHF).

2.1.1. Zone

In Figure 3 the view of the investigated zone is shown. No adsorption cooling elements are integrated into the east and west façades in the reference scenario. In the photovoltaic scenarios, the adsorption cooling elements are replaced by PV elements. Only one floor of a building is investigated. The building has a quadratic floor plan; the ceiling height is $h = 3$ m and the edge lengths $b = \frac{4}{AV}$ are defined via the AV ratio. The south façade is orthogonal to the south. The layer structures and material properties of the windows, external walls, and internal walls (ceiling and floor) are defined in Appendix A.1.

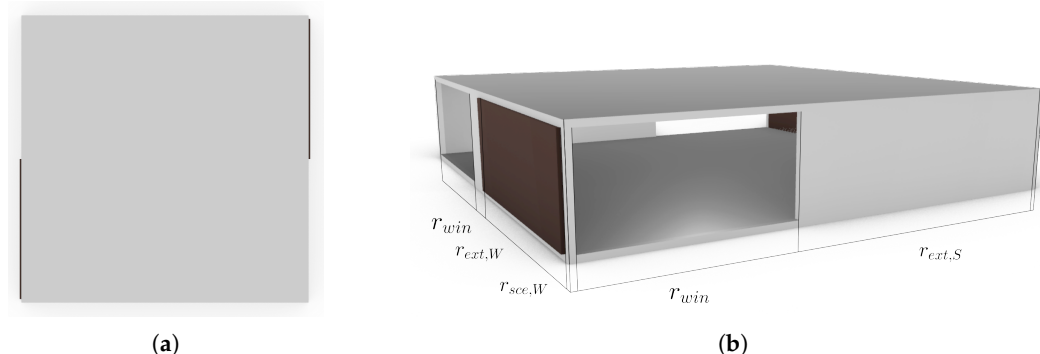


Figure 3. Visual representation of the investigated scene for the adsorption cooling scenario from two viewpoints. The solar cooling elements are highlighted in dark colour. (a) Plan view. (b) Perspective.

In each orientation, a window is placed. The window area is defined by the window-to-wall ratio $r_{win} = 0.4$. No window shading elements are used, which represents a conservative estimate for the cooling performance.

Following the determination of area ratios for windows r_{win} and solar cooling elements $r_{sce,j}$ for each orientation j , the remaining façade proportion is defined by an external insulated wall $r_{ext,j}$. The area of the solar cooling elements is specified based on the total façade area with $A_{sce,j} = b h r_{sce,j}$. The window and insulated wall elements are modelled according to the thermal network approach as per ISO 52022-3 [25].

Short- and long-wave radiative exchange is modelled using a view factor matrix. The view factors are created according to the examples in the book [26]. The sum rule is used to validate the view factor matrix. The view factor matrix is created for the reference scenario without integrated solar cooling elements and remains constant for other scenarios.

It is assumed that the construction of the solar cooling elements does not affect the internal distribution of short- and long-wave radiation.

2.1.2. External Heat Fluxes

The external heat fluxes comprise internal gains, heat input from a heat pump, cooling input from a compression chiller, and a ventilation system.

When the room is occupied ($occ > 0$), an internal heat release from occupants of 7 W m^{-2} is convectively emitted. Additionally, waste heat from machines of 15 W m^{-2} is considered. These settings were chosen according to DIN 18599-10 (Table A.2, [27]), assuming a high occupancy density.

To provide potential heating demand, a heat pump with a constant coefficient of performance ($cop = 4$) is implemented. Furthermore, a compression chiller is considered, modelled with a constant energy efficiency ratio eer which is subject to parameter variation. The input signals u_{HP} and u_{CH} are scaled with the nominal power $\dot{q}_{nom} = 300 \text{ W m}^{-2}$.

The ventilation concept includes a fan in both the supply and exhaust air, as well as a cross-flow heat exchanger with a bypass damper u_{bypass} parameterised with a recovery rate of $\Phi = 0.7$. The following properties are assumed for the fans ($P_{nom} = 45 \text{ W}$; $\dot{V}_{nom} = 610 \text{ m}^3 \text{ h}^{-1}$). The current power demand is calculated from the specified air change rate acr_{ven} . Additionally, a constant infiltration rate of $acr_{inf} = 0.45 \text{ h}^{-1}$ is assumed.

2.1.3. Dynamic Optimisation

Within the dynamic optimisation, the nonlinear optimisation problem, cf. Equation (1), is solved. The objective function consists of the electrical powers of the heat pump P_{HP} , the compression chiller P_{CH} , and the ventilation P_{AHU} . The system dynamics f_{s1} is derived from the Modelica model.

$$\begin{aligned} \underset{\mathbf{u}_{s1}}{\text{minimize}} \quad & E_{s1} = \int_{t=0}^{t=t_1} P_{HP} + P_{CH} + P_{AHU} dt \\ \text{subject to} \quad & \dot{\mathbf{x}}_{s1} = f_{s1}(\mathbf{x}_{s1}, \mathbf{u}_{s1}, \mathbf{d}), \\ & \mathbf{x}_{s1}(t) \in \mathbb{X}_{s1}(t), \\ & \mathbf{u}_{s1}(t) \in \mathbb{U}_{s1}(t) \end{aligned} \quad (1)$$

$$\mathbf{x}_{s1} = \{T_z, \bar{T}_{ext}^T, \bar{T}_{int}^T\}^T \quad (2)$$

$$\mathbf{u}_{s1} = \{u_{HP}, u_{CH}, u_{bypass}, acr_{ven}\}^T \quad (3)$$

$$\mathbf{d} = \{occ, T_{amb}, T_{bs}, \bar{I}_{gti}^T\}^T \quad (4)$$

The state variables are the temperature of the room T_z , and the external $\bar{T}_{ext}$ and internal wall layers $\bar{T}_{int}$, from floor and ceiling. The system inputs are the signals for controlling the heat pump u_{HP} and compression chiller u_{CH} , as well as those for the ventilation system, the bypass damper u_{bypass} , and the air change rate acr_{ven} . The disturbances $\mathbf{d}$ are defined by the occupancy signal occ , the ambient temperature T_{amb} , the black sky temperature T_{bs} , and the global irradiance on all four inclined surfaces $\bar{I}_{gti}$. An occupancy of the room is assumed from 7 a.m. to 6 p.m. The room temperature is set to a value of $T_z(0) = 21 \text{ }^\circ\text{C}$ at the beginning of the simulation. All other initial temperatures are not specified but are iteratively determined by the Modelica solver.

The following state and input constraints apply, chosen in accordance with DIN 18599-10 (Table A.2, [27]):

$$\mathbb{X}_{s1}(t) = \left\{ T_z \in \begin{cases} [21^\circ\text{C}, 24^\circ\text{C}] & occ(t) > 0 \\ [16^\circ\text{C}, 30^\circ\text{C}] & \text{else} \end{cases} \right\} \quad (5)$$

$$\mathbb{U}_{s1}(t) = \left\{ \begin{array}{l} u_{HP} \in [0, 1] \\ u_{CH} \in [0, 1] \\ u_{bypass} \in [0, 1] \\ acr_{ven} \in \begin{cases} [2, 8] & occ(t) > 0 \\ [0, 8] & \text{else} \end{cases} \end{array} \right\} \quad (6)$$

2.2. Adsorption Cooling Scenario (2ACE)

Compared to the reference scenario, two adsorption cooling elements are additionally integrated into the west and east façades and connected to the zone in the adsorption cooling scenario. The system scheme is shown in Figure 2b. These elements reduce the cooling capacity required by compression cooling. Their areas are defined via the area ratios to the total façade area ($r_{sce,W}$, $r_{sce,E}$), which are subject to parameter variation.

The system diagram of one adsorption cooling element is shown in Figure 4. This consists of a collector, adsorber, condenser, and evaporator. The collector is connected to the ambient temperature T_{amb} and the respective irradiance I_{gti} . When the collector is irradiated, it drives the desorption process from the adsorber to the condenser, and the thermochemical cold storage is being charged. Subsequently, if cooling is required, valves are opened and water is driven from the evaporator to the adsorber. The evaporator cools down, stores excess energy, and provides cooling to the room when needed. First, it was intended that the adsorption cooling element will be integrated into a wall construction, for which the wall temperature node T_w is provided. However, in this study, it is set to a constant $T_w = 21^\circ\text{C}$. The models of all components are described in the following subsections. Subsequently, the nonlinear optimisation problem is summarised.

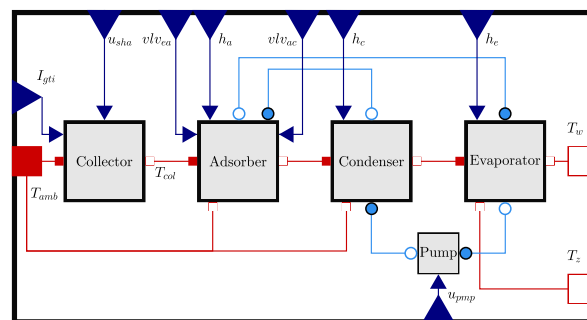


Figure 4. Block diagram of one adsorption cooling element

2.2.1. Collector

Following the relationship in Equation (7), the collector is modelled.

$$\dot{Q} = u_{sha}\eta_0 I_{gti} - c_1(T_{col} - T_{amb}) - c_2(T_{col} - T_{amb})^2 \quad (7)$$

Data from an evacuated flat plate collector are assumed ($\eta_0 = 0.737$, $c_1 = 0.504 \text{ W m}^{-2} \text{ K}$, and $c_2 = 0.006 \text{ W m}^{-2} \text{ K}^2$). These values were taken from the study [28]. A shading factor u_{sha} is considered, according to the studies [13,18].

2.2.2. Base Model

The adsorber, condenser, and evaporator all extend a common base model, see Figure 5a. This model defines the impact of incoming temperature, e.g., from the collector on the capacity of the aluminium casing C_{cas} , and the heat transfer from the casing to the adsorbent or vapour–liquid equilibrium (VLE) G_{cas} . Heat exchange with the environment or the room can be adjusted via the dynamic heat transfer coefficient h , allowing for suitable heat exchanger determination from the determined time series. Furthermore, heat transfer from the casing to the next element is defined by an insulation layer G_{ins} .

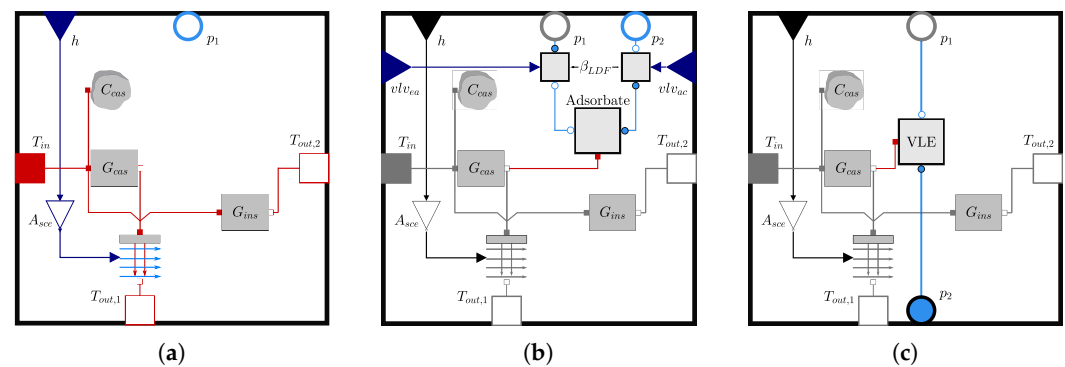


Figure 5. Block diagram of the base model, adsorber, and condenser. (a) Base model. (b) Adsorber. (c) Evaporator and condenser.

The casing material is consistently aluminium, and the insulation layer is a vacuum insulation panel with a thickness of 2 cm. Material and geometric properties were created based on the geometries presented in the study [28]. Table A5 provides an overview of the used parameter values (C_{cas} , G_{cas} , and G_{ins}), which are related to the area of the solar cooling element A_{sce} .

2.2.3. Adsorber

The adsorber model is depicted in Figure 5b. It extends the base model with the adsorbate model and diffusion resistances to the evaporator and condenser, implemented using the experimentally validated SorpLib (v1) [15] Modelica library.

The adsorbate model solves the mass and energy balance of the adsorbate, investigating the working pairs Zeolite 13X–water and Silica Gel SG123–water. The Dubinin–Astakhov equation is used as the characteristic curve, with adsorbent mass determined via the bulk density ρ_{bulk} and cavity volume $V_{cav,a}$. The cavity volume, related to the element area, is $\frac{V_{cav,a}}{A_{sce}} = 6.05$ cm.

Mass flows due to diffusion are described according to Glueckauf’s linear driving force approach, cf. Equation (8). Consistent with the thesis [21], no diffusion resistance β_{darcy} due to pressure loss is considered. The two mass flows per adsorption cooling element are regulated via a continuous valve signal, with constraints ensuring mass flow only occurs from the evaporator to the adsorber and from the adsorber to the condenser.

$$\beta_{LDF} = \frac{60D_{eff}}{d_{sph}^2} \quad (8)$$

The coefficients of the Dubinin–Astakhov equation and the material parameters of Zeolite 13X and Silica Gel SG123 are experimentally validated and were taken from the thesis [21] and are given in Table A6. During this study, the Dubinin–Astakhov equation proved to converge more reliably to a solution for the dynamic optimisation problem than the Dubinin–Lorenzian Cumulative equation. However, different characteristic curves

were used in the thesis [21]; thus, the coefficients of the Dubinin–Astakhov equation were adjusted to match the given characteristic curves. Furthermore, the bulk density ρ_{bulk} is not provided in the thesis [21]. Therefore, the bulk density of Silica Gel SG123 was taken from the study [29], and the bulk density of Zeolite 13X was determined based on the masses given in the thesis [21].

2.2.4. Evaporator and Condenser

The evaporator and condenser model is depicted in Figure 5c. They consist of a cavity volume V_{cav} , which is surrounded by a casing. The cavity volume $\frac{V_{cav}}{A_{sce}} = d_{cav}$ is given by the thickness d_{cav} and the element area A_{sce} . A thickness of $d_{cav,c} = 1$ cm was assumed for the condenser and $d_{cav,e} = 10$ cm for the evaporator. The cavity volume contains water in vapour–liquid equilibrium (VLE), implemented using the SorpLib Modelica Library [15] (Version 1). The liquid condensing in the condenser is pumped back to the evaporator by a pump if required, although this functionality is not utilised as only one day is considered, with the pump signal pmp continuously set to zero. The fluid properties of water were taken from the NIST Chemistry WebBook [30], fitted to a Taylor series of order $n = 5$, and integrated into the adsorber, condenser, and evaporator models.

2.2.5. Dynamic Optimisation

The nonlinear optimisation problem for the adsorption cooling scenario, cf. Equation (9), extends the optimisation problem, cf. Equation (1).

$$\begin{aligned} & \underset{\mathbf{u}_{s1}, \mathbf{u}_{s2,W}, \mathbf{u}_{s2,E}}{\text{minimize}} & E_{s2} &= \int_{t=0}^{t=t_1} P_{HP} + P_{CH} + P_{AHU} dt \\ & \text{subject to} & \{\dot{\mathbf{x}}_{s1}^T, \dot{\mathbf{x}}_{s2,W}^T, \dot{\mathbf{x}}_{s2,E}^T\}^T &= f_{s2}(\mathbf{x}_{s1}, \mathbf{x}_{s2,W}, \mathbf{x}_{s2,E}, \mathbf{u}_{s1}, \mathbf{u}_{s2,W}, \mathbf{u}_{s2,E}, \mathbf{d}), \\ & & \mathbf{x}_{s1}(t) &\in \mathbb{X}_{s1}(t), \\ & & \mathbf{u}_{s1}(t) &\in \mathbb{U}_{s1}(t), \\ & & \mathbf{u}_{s2,j}(t) &\in \mathbb{U}_{s2,j}(t) \quad \forall j \in [W, E], \\ & & \theta_j(0) &= \theta_j(t_1) \quad \forall j \in [W, E], \\ & & \dot{m}_{ea,j}(t) &> 0 \quad \forall j \in [W, E], \\ & & \dot{m}_{ac,j}(t) &> 0 \quad \forall j \in [W, E] \end{aligned} \quad (9)$$

$$\mathbf{x}_{s2,j} = \{T_{cas,a,j}, T_{a,j}, \theta_j, T_{cas,c,j}, T_{c,j}, \rho_{c,j}, T_{cas,e,j}, T_{e,j}, \rho_{e,j}\}^T \quad (10)$$

$$\mathbf{u}_{s2,j} = \{u_{sha,j}, h_{a,j}, h_{e,j}, vl_{v_{ea,j}}, vl_{v_{ac,j}}\}^T \quad (11)$$

Adding the two adsorption cooling elements introduces nine additional states $\mathbf{x}_{s2,j}$ per element j . These comprise the temperatures of the casings, the adsorbate, and the VLE, as well as the relative loading θ_j of the adsorbate and the densities of the VLE mixtures ρ . Initially, the two adsorber temperatures are set to 60 °C and the temperatures of the condenser and evaporator to 21 °C. The initial densities of the vapour–liquid equilibria are determined via a liquid volume fraction of 0.95. The relative initial loadings θ_j are determined based on an initial loading study presented in the following subsection.

Furthermore, five additional inputs $\mathbf{u}_{s2,j}$ are added for each adsorption cooling element. The manipulated variables are the shading factor of the collector $u_{sha,j}$, the heat transfer coefficients for adsorber and evaporator ($h_{a,j}, h_{e,j}$), and the valve positions from and to the adsorber ($vl_{v_{ac,j}}, vl_{v_{ea,j}}$). For simplicity, the heat transfer coefficient from the condenser to the environment is set to a constant value of $h_{c,j} = 200 \text{ W m}^{-2} \text{ K}$.

A final state constraint applies to the loadings to ensure comparability of the cooling storage potentials. Additionally, a mass flow constraint is set for each element from the evaporator to the adsorber and from the adsorber to the condenser to prevent backflow. Furthermore, the following input constraints apply for each element j :

$$\mathbb{U}_{s2,j}(t) = \left\{ \begin{array}{l} u_{sha,j} \in [0, 1] \\ h_{a,j} \in [0, 200] \\ h_{e,j} \in [0, 200] \\ vl v_{ea,j} \in [0, 1] \\ vl v_{ac,j} \in [0, 1] \end{array} \right\} \quad (12)$$

2.2.6. Convergence Assurance

Due to numerical instability in the dynamic optimisation problems of the 2ACE scenario, some samples fail to converge. In such cases either the iterations exceed the standard limit `ipoptMaxIterations` = 3000 or the error “Restoration_Failed” is reported, relating to issues in satisfying all boundary conditions. Besides this, the convergence is highly related to the problem size, mainly defined by the time step Δt and the constraints as well as the initial conditions, mainly the initial relative loadings.

Various measures were taken in this study to ensure the convergence of the dynamic optimisation of the 2ACE scenario:

- The pump signal and the heat transfer of the condenser were set to constant values.
- If $r_{sce,W} = 0$ or $r_{sce,E} = 0$, reduced system models were created, reducing the number of inputs, states, and constraints.
- The time step of the adsorption cooling scenario simulations was increased from 15 to 60 min to reduce the problem size.
- An initial loading study was introduced for each data point in the result figures. Incidentally, this leads to a reduction in energy consumption.
- If an initial loading study resulted in a converged data point with unrealistically high self-sufficiency, which occurred in approximately five out of 236 data points, the calculation was repeated.

The initial loading study conceptually extends the nonlinear program, cf. Equation (9), to include the two relative initial loadings. If dynamic optimisation does not converge, the energy consumption of the reference scenario E_{s1} is applied. The following optimisation problem is solved:

$$\begin{array}{ll} \underset{\theta_W(0), \theta_E(0)}{\text{minimize}} & E = \begin{cases} \text{if converged} & E_{s2} \\ \text{else} & E_{s1}(eer, AV) \end{cases} \\ \text{subject to} & \theta_j(0) \in [0, 1] \quad \forall j \in [W, E] \end{array} \quad (13)$$

All initial loading studies are conducted with the optimisation framework Optuna [31] with the attributes `n_startup_trials` = 20 and `n_trials` = 50.

2.3. Photovoltaic Scenario (2PV)

The system configuration for the photovoltaic scenario is shown in Figure 2c. Here, two PV modules are integrated into the west and east façades instead of the adsorption cooling elements. Their areas are defined via the area ratios to the total façade area ($r_{sce,W}$, $r_{sce,E}$). The electricity production of these elements reduces the electricity consumption. Excess electricity is not used or fed into the grid.

The electrical power output from both PV modules is determined using the temperature-dependent model (Equation (1-2), [32]). The parameter values are given in Table A7.

2.3.1. Dynamic Optimisation

Within the dynamic optimisation, the nonlinear optimisation problem, cf. Equation (14), is solved. This differs from the optimisation problem, cf. Equation (1), in the objective function in that the PV feed-in P_{PV} is subtracted from the demand. As no battery and excess electricity production are considered, the PV feed-in is only taken into account as long as the objective function remains greater than zero. This is regulated by the additional input u_{s3} and the constraints. Otherwise, the same states, inputs, and constraints apply as for the reference scenario.

$$\begin{aligned} & \underset{\mathbf{u}_{s1}, u_{s3}}{\text{minimize}} && E_{s3} = \int_{t=0}^{t=t_1} P_{HP} + P_{CH} + P_{AHU} - P_{PV}(1 - u_{s3}) dt \\ & \text{subject to} && \dot{\mathbf{x}}_{s1} = f_{s1}(\mathbf{x}_{s1}, \mathbf{u}_{s1}, \mathbf{d}), \\ & && \mathbf{x}_{s1}(t) \in \mathbb{X}_{s1}(t), \\ & && \mathbf{u}_{s1}(t) \in \mathbb{U}_{s1}(t), \\ & && u_{s3}(t) \in [0, 1], \\ & && 0 \leq P_{HP} + P_{CH} + P_{AHU} - P_{PV}(1 - u_{s3}) \end{aligned} \quad (14)$$

2.4. Photovoltaic Plus Battery Scenario (2PVB)

The fourth scenario differs from the 2PV scenario by the addition of a battery. The PV yield is modelled identically. A PV module is also integrated into the west and east façades. Their areas are defined by the area ratios to the total façade area ($r_{sce,W}$, $r_{sce,E}$).

2.4.1. Dynamic Optimisation

Within the dynamic optimisation, the nonlinear optimisation problem, cf. Equation (15), is solved. This differs from the optimisation problem, cf. Equation (14), in the objective by not regulating the PV production with the signal u_{s3} . Instead, the discharge power P_{B-} of an additional battery is optimised and integrated into the objective. The upper limit of the discharge power is chosen such that it is not reached for any of the examined data points. Periodic boundary conditions for the state of charge SOC are set. Initially, the dynamic optimisation starts from a state of charge $SOC(0) = 0$ kWh. Negative states of charge are allowed. Subsequently, the initial state of charge $SOC(0)$ and the maximum stored energy SOC_{max} are determined by shifting the charge curve upwards by the minimum state of charge. Otherwise, the same states, inputs, and constraints apply as in the reference scenario.

$$\begin{aligned} & \underset{\mathbf{u}_{s1}, P_{B-}}{\text{minimize}} && E_{s4} = \int_{t=0}^{t=t_1} P_{HP} + P_{CH} + P_{AHU} - P_{B-} dt \\ & \text{subject to} && \dot{\mathbf{x}}_{s1} = f_{s1}(\mathbf{x}_{s1}, \mathbf{u}_{s1}, \mathbf{d}), \\ & && \mathbf{x}_{s1}(t) \in \mathbb{X}_{s1}(t), \\ & && \mathbf{u}_{s1}(t) \in \mathbb{U}_{s1}(t), \\ & && \dot{SOC} = P_{PV} - P_{B-}, \\ & && SOC(0) = SOC(t_1), \\ & && P_{B-}(t) \in [0, 50] \text{ kW}, \\ & && 0 \leq P_{HP} + P_{CH} + P_{AHU} - P_{B-} \end{aligned} \quad (15)$$

3. Results

In this section, the results of several parameter variations are presented. These variations include the area ratios of the respective solar cooling elements in the west and east façades ($r_{sce,j} = \frac{A_{sce,j}}{bh}$), the energy efficiency ratio of the compression cooling eer , and the façade area-to-room volume ratio AV . These investigations are applied to all four presented scenarios.

The self-sufficiency level SL is introduced as the central comparison metric, cf. Equation (16). It describes to what extent the electrical energy consumption of the considered scenario is lower than that of the reference scenario. It thus represents the ability of a scenario to supply the necessary amount of power independently of the grid. At 100 %, no additional external power is needed, the power produced equals the power consumed. At 0 %, the considered scenario offers no advantage.

$$SL(r_{sce,W}, r_{sce,E}, eer, AV) = \frac{E_{s1}(eer, AV) - E(r_{sce,W}, r_{sce,E}, eer, AV)}{E_{s1}(eer, AV)} \quad (16)$$

In the first sub chapter, the required energy consumption of the reference scenario at standard conditions are presented. Subsequently, the impact of the parameters ($r_{sce,W}$, $r_{sce,E}$, eer , and AV) on the self-sufficiency level of all investigated scenarios is examined.

Given that the area ratios ($r_{sce,W}$ and $r_{sce,E}$) are the subject of parameter variation, they are determined from intermediate variables that are easier to understand. These intermediate variables are the balance ratio $r_{bal} = \frac{r_{sce,E}}{r_{tot}}$ and the total area ratio $r_{tot} = r_{sce,W} + r_{sce,E}$. The balance ratio indicates how the total area is distributed between the west and east elements. If the total area is assigned to the west element, the balance ratio is $r_{bal} = 0$. If the focus is solely on the east element, the balance ratio is $r_{bal} = 1$. The total area ratio r_{tot} indicates the overall capacity for solar cooling. Due to the constant window area ratios with $r_{win} = 0.4$, the area ratios of the solar cooling elements ($r_{sce,W}$ and $r_{sce,E}$) are limited. Therefore, not all balance ratios are evaluated for a total area ratio $r_{tot} > 0.6$.

3.1. Energy Consumption of the Reference Scenario at Standard Conditions

Figure 6 presents the optimal time series of the reference scenario for the standard conditions ($eer = 2.5$ and $AV = 0.25$). Figure 6a shows the total electrical energy consumption, which increases during the occupancy period and amounts to $E_{s1} = 27.5$ kW h by the end of the day. Figure 6b displays the floor area-specific thermal cooling power of the compression chiller, which only occurs during occupancy. The lowest value is $\frac{\dot{Q}_{CH}}{A_{floor}} = -29.4$ W m⁻². Figure 6c shows the room temperature, the upper and lower room temperature constraints, and the ambient temperature. Starting from the initial value, the room temperature remains near the upper limit for most of the occupancy period, with constraints being met. Figure 6d depicts the bypass signal, the air change rate, and its upper and lower limits. The air change rate increases when the room temperature reaches the upper limit and cooling power is required. Otherwise, it is tied to the lower constraint. The bypass is fully utilised during the morning cooling period but is not relevant in other time periods when the air change rate is zero.

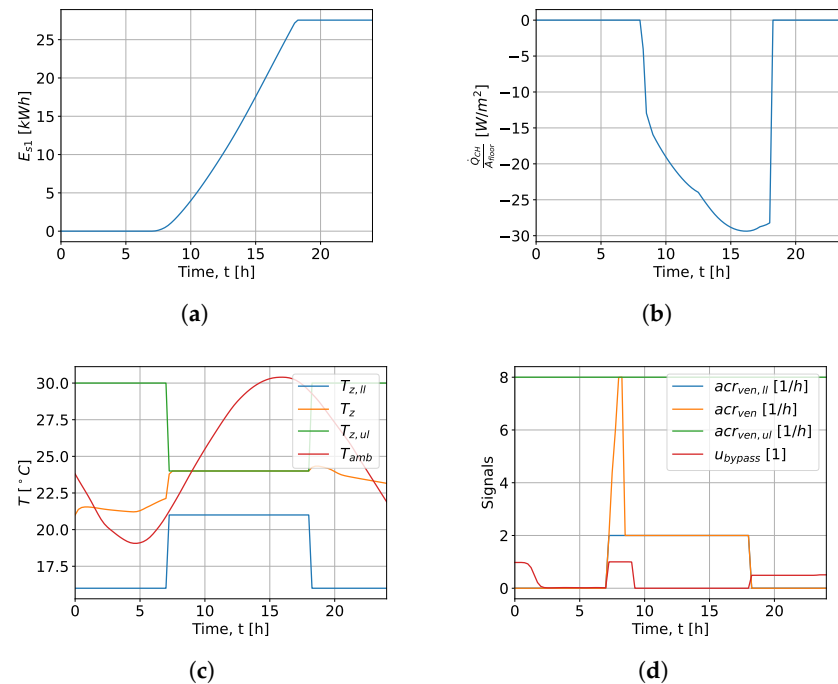


Figure 6. Optimal trajectories of the reference scenario at standard conditions ($eer = 2.5$ and $AV = 0.25$). (a) Total electrical energy consumption. (b) Specific thermal cooling power. (c) Temperatures. (d) Air-handling unit signals.

3.2. Influence of Adsorbent and Both Area Fractions (r_{bal} , r_{tot}) on the 2ACE Scenario

For this parameter variation, the energy efficiency ratio of the compression chiller and the façade area-to-room volume ratio are kept constant at standard conditions ($eer = 2.5$ and $AV = 0.25$).

The results for the self-sufficiency level for both adsorbent materials are presented in Figure 7. The maximum self-sufficiency level at a constant total area fraction is indicated by a star. Applying the initial loading study to all 144 data points in Figure 7 requires a computation time of 11.8 days.

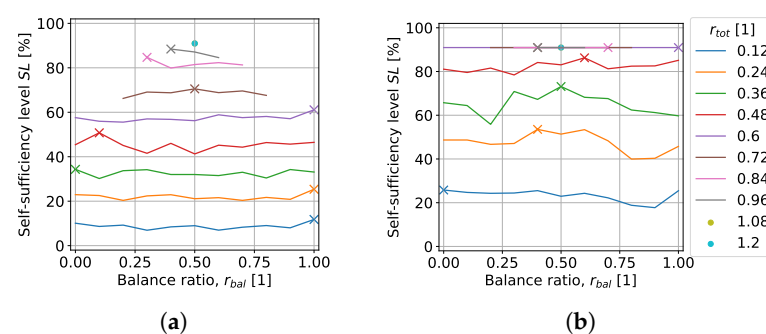


Figure 7. Self-sufficiency level of the 2ACE scenario for both adsorbents, different balance ratios r_{bal} , and total element area r_{tot} . (a) Zeolite 13X. (b) Silica Gel SG123.

For the adsorbent Zeolite 13X, cf. Figure 7a, the self-sufficiency level rises with increasing total surface area ratio r_{tot} . When $r_{tot} > 0.96$, equivalent to a total area $A_{sce,tot} = 46.08 \text{ m}^2$, the maximum self-sufficiency level $SL_{max} = 91.0 \%$ is attained. At constant total area r_{tot} , the self-sufficiency level shows no pronounced maximum behaviour. No clear trend is discernible with respect to the balance ratio r_{bal} .

In comparison, the use of the adsorbent Silica Gel SG123, cf. Figure 7b, exhibits a greater increase in the self-sufficiency level with total area. Beyond a ratio of $r_{tot} > 0.48$,

the same maximum self-sufficiency level $SL_{max} = 91.0\%$ is achieved. Until the maximum self-sufficiency level is reached, using Silica Gel SG123 therefore results in near twice the self-sufficiency for the same total area r_{tot} . Regarding the balance ratio, no pronounced maximum behaviour is observed either. A balanced ratio $r_{bal} = 0.5$ tends to lead to increased self-sufficiency compared to exclusive distribution on one orientation.

In Figure 8, the relative initial loadings obtained from the initial loading studies are now considered, with the initial loadings for the west adsorber represented by a solid line and for the east adsorber by a dashed line.

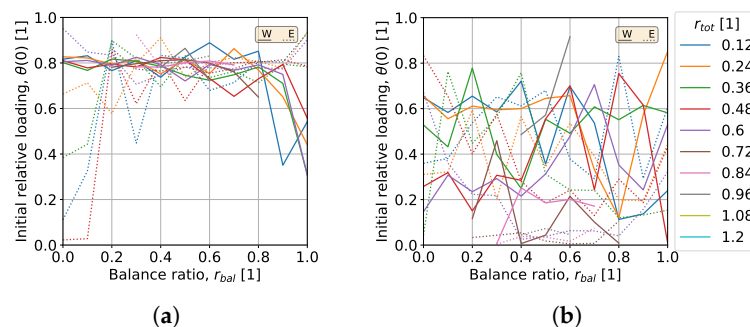


Figure 8. Initial relative loading $\theta(0)$ for both adsorbent materials, different balance ratios r_{bal} , and total element area r_{tot} . The relative loading of the west element is solid and east dotted. (a) Zeolite 13X. (b) Silica Gel SG123.

For the adsorbent Zeolite 13X, cf. Figure 8a, a relative initial loading of $\theta(0) = 0.8$ for both the east and west adsorbers tends to yield optimal results within the initial loading studies. However, this applies only to a limited extent within the middle range of the balance ratio r_{bal} . No clear dependence on the total area ratio r_{tot} is discernible. For the adsorbent Silica Gel SG123, cf. Figure 8b, initial loadings $\theta(0) < 0.8$ are predominantly chosen, with no clear correlation to the balance ratio r_{bal} or the total area ratio r_{tot} observable.

3.3. Influence of Time Step Δt and Heat Transfer Coefficient $\frac{G_{cas,a}}{A_{sce}}$ on the 2ACE Scenario

Table 1 presents the results of the analysis concerning the time step Δt of the dynamic optimisation problem, cf. Equation (9). The remaining parameters ($r_{bal} = 0.5$, $r_{tot} = 0.36$, $eer = 2.5$, and $AV = 0.25$) were held constant. The heat transfer coefficient $\frac{G_{cas,a}}{A_{sce}}$ is determined according to Table A5. Silica Gel SG123 was employed as the adsorbent.

Table 1. Analysis of the time step Δt of the dynamic optimisation problem, cf. Equation (9).

Δt /[min]	60	45	30	15
$n_{success}$ /[-]	20	11	1	0
t_{ils} /[h]	2.1	2.5	3.0	5.1
E_{s2} /[kWh]	8.0	6.7	(14.1)	(27.5)

The results in Table 1 indicate that not all of the 50 trials successfully converged during the initial loading study. This number of successful trials $n_{success}$ decreases with a decreasing time step. For a time step of $\Delta t = 30$ min, only one of 50 samples converges, and none converge for $\Delta t = 15$ min. Concurrently, the computational time of the initial loading study, t_{ils} , increases as the time step decreases. Energy consumption decreases from $\Delta t = 60$ min to $\Delta t = 45$ min but then increases again. The last two values are placed in brackets due to the small number of successfully converged samples.

The influence of the critical heat transfer coefficient between collector and adsorbent $\frac{G_{cas,a}}{A_{sce}}$ is investigated in Figure 9. For this analysis, the time step is held constant at $\Delta t = 60$ min.

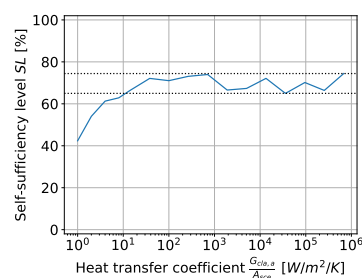


Figure 9. Influence of the critical heat transfer coefficient between the collector and adsorbent on the self-sufficiency level. Self-sufficiency results as blue line and range 65.0–74.4 % as dotted line.

The results in Figure 9 demonstrate that the self-sufficiency level of the 2ACE scenario increases with a higher critical heat transfer coefficient $\frac{G_{cas,a}}{A_{sce}}$. Beyond a value of $\frac{G_{cas,a}}{A_{sce}} = 10 \text{ W m}^{-2} \text{ K}$, the self-sufficiency level stabilises within a range of 65.0–74.4 %.

3.4. Influence of Both Area Fractions (r_{bal} , r_{tot}) on the 2PV and 2PVB Scenarios

Figure 10 presents the results of the parameter variation in the area fractions (r_{bal} , r_{tot}) on the photovoltaic scenarios. Calculating all 272 data points in Figure 10 requires approximately 5.5 h.

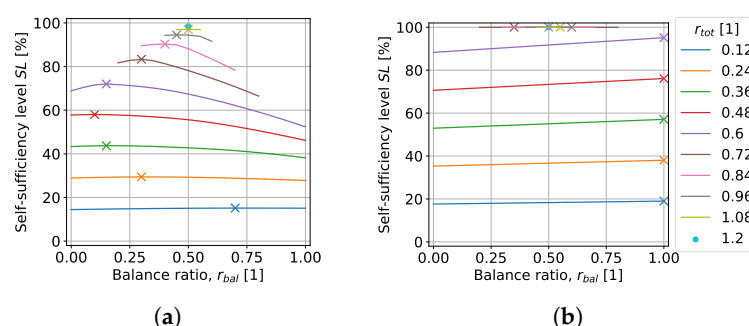


Figure 10. Self-sufficiency level of the 2PV and 2PVB scenarios for different balance ratios r_{bal} and total element area r_{tot} . (a) 2PV scenario. (b) 2PVB scenario.

3.4.1. Photovoltaic Scenario (2PV)

Figure 10a shows the results of the self-sufficiency level of the 2PV scenario when varying the balance and total area ratios. As with the adsorption cooling scenario, increasing the total area fraction r_{tot} generally leads to increased self-sufficiency. The 2PV scenario delivers lower self-sufficiency than the adsorption cooling scenario with the adsorbent Silica Gel SG123, cf. Figure 7b, for total area ratios $r_{tot} < 0.8$. Subsequently, the self-sufficiency level increases to a value higher than the 2ACE scenario. The maximum self-sufficiency level $SL_{max} = 98.5\%$ is achieved at the maximum area ratio $r_{tot} = 1.2$. For constant total area ratios, a continuous and pronounced maximum behaviour of the self-sufficiency is observed. The maximum curve is less pronounced for small total surface areas and subsequently more pronounced and shifted towards the western façade element. As the total area ratio continues to increase, the maximum shifts towards an even distribution of element areas $r_{bal} = 0.5$. Generally, a purely eastern distribution of the total area leads to a lower self-sufficiency level than a purely western distribution; the maximum always lies in between.

3.4.2. Photovoltaic Plus Battery Scenario (2PVB)

Figure 10b shows the results for the 2PVB scenario. The self-sufficiency increases with the total area ratio of the two elements, as with the other two scenarios. From a total area ratio $r_{tot} > 0.6$, complete self-sufficiency $SL = 100\%$ applies consistently. However, up to

this total area ratio, a purely eastern distribution results in higher self-sufficiency than for the western element or a balance between them. This maximum prominence increases slightly with the total area ratio r_{tot} .

To enable dynamic optimisation without specifying a start and end value for the battery capacity, the start and end capacity were set to zero, and a negative battery capacity was permitted. Following the dynamic optimisation, the state-of-charge profile of the battery is corrected by the minimum value, from which the initial $SOC(0)$ and maximum SOC_{max} state of charge were derived, cf. Figure 11.

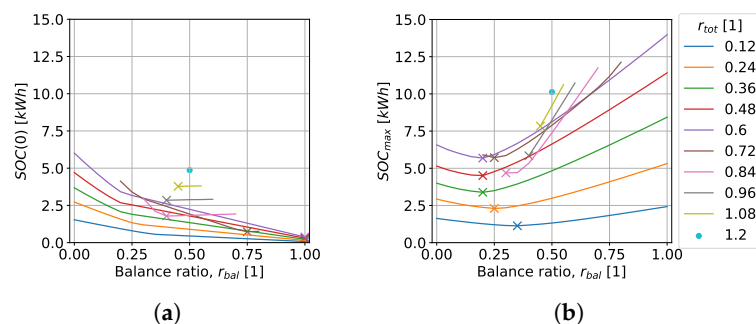


Figure 11. Results of the initial and maximum battery capacity of the 2PVB scenario for both area fractions (r_{bal} , r_{tot}). (a) Initial battery capacity. (b) Maximum battery capacity.

The behaviour of the initial battery capacity $SOC(0)$, cf. Figure 11a, is divided by the total area ratio $r_{tot} \leq 0.72$. Up to the ratio $r_{tot} \leq 0.72$, a clear minimum behaviour is observed with the balance ratio r_{bal} . The initial battery capacity decreases with an increasing area focus on the east element. Above an area ratio $r_{tot} > 0.72$, a minimum behaviour is observed within the range of the middle balance ratios.

The maximum capacity SOC_{max} is shown in Figure 11b. For a total area ratio $r_{tot} < 0.72$, it exhibits a pronounced minimum behaviour between a balance ratio of 0.2 to 0.4 and then rises sharply with the balance ratio. Above a total area ratio of $r_{tot} > 0.72$, the initially western focus crosses a saddle point. The minimum now shifts back to a balance ratio $r_{bal} = 0.5$.

3.5. Influence of the Energy Efficiency Ratio (*eer*)

This section investigates the influence of the energy efficiency ratio of the compression chiller. The balance ratio is held constant at $r_{bal} = 0.5$ and the façade area-to-room volume ratio at $AV = 0.25$. The total area ratio of both elements r_{tot} and the energy efficiency ratio *eer* are varied. This analysis serves to enable an assessment of potentially temperature-dependent rather than constant energy efficiency ratios.

The results of the reference scenario are presented in Table 2. As the energy efficiency ratio increases, the energy consumption of the reference scenario decreases, requiring less electricity for the same cooling capacity.

Table 2. Total daily electricity consumption of the reference scenario E_{s1} for different energy efficiency ratios *eer*.

<i>eer</i> /[1]	1.50	2.00	2.50	3.00	3.50
E_{s1} /[kWh]	43.9	33.7	27.5	23.4	20.5

In Figure 12, the results of the parameter variation are presented for all three scenarios. For the adsorption cooling scenario, the adsorbent Silica Gel SG123 was applied. As in the previous parameter variation, an increase in self-sufficiency is observed with the total area of both elements r_{tot} . For the 2ACE scenario, a slight influence of the energy efficiency ratio

of the supporting compression chiller is shown. With an increasing energy efficiency ratio, the self-sufficiency decreases slightly. For the other scenarios, the energy efficiency ratio eer has a significant influence. With an increasing ratio, the self-sufficiency increases. This leads, in the 2PVB scenario, to complete self-sufficiency being achieved with a decreasing total area ratio. In the range $r_{tot} \leq 0.5$, the 2ACE scenario consistently increases faster than the PV scenario. Consequently, the 2ACE scenario requires less total area to achieve the same self-sufficiency level. This also applies to the 2PVB scenario up to an energy efficiency ratio $eer < 3$. However, compared to the photovoltaic scenarios, the 2ACE scenario is limited and never reaches complete self-sufficiency $SL = 100\%$, as is the case with the 2PVB scenario.

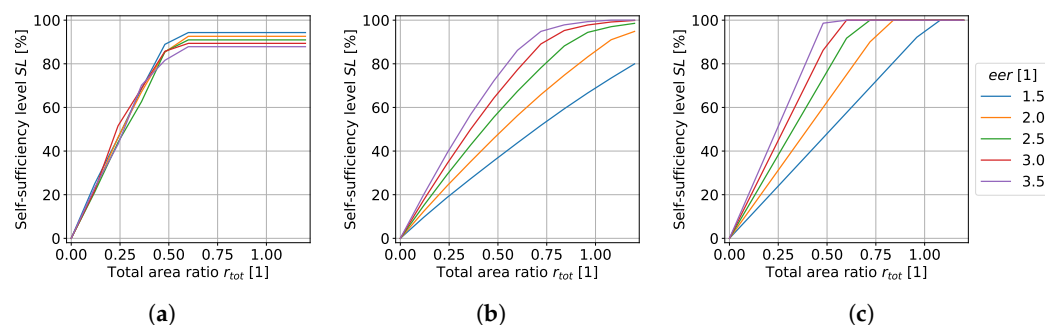


Figure 12. Self-sufficiency level for all scenarios for different energy efficiency ratios eer and total element area r_{tot} . (a) 2ACE scenario. (b) 2PV scenario. (c) 2PVB scenario.

3.6. Influence of the Façade Area-to-Room Volume Ratio (AV)

This section investigates the influence of the building type. The balance ratio is held constant at $r_{bal} = 0.5$ and the energy efficiency ratio at $eer = 2.5$. The total area ratio of both elements r_{tot} and the façade area-to-room volume ratio AV are varied. This serves to classify the solar cooling potential for different building types.

The results for the reference scenario are given in Table 3. With a decreasing AV ratio, the building's edge length, façade area, floor area, and energy consumption increase. The floor area increases more strongly than the façade area.

Table 3. Total daily electricity consumption of the reference scenario E_{s1} for different façade area-to-room volume ratios AV .

$AV / [\frac{1}{m}]$	0.50	0.25	0.12	0.06	0.03
$b / [m]$	8	16	32	64	128
$A_{faades} / [m^2]$	96	192	384	768	1536
$A_{floor} / [m^2]$	64	256	1024	4096	16,384
$E_{s1} / [kWh]$	9.9	27.6	88.3	311.7	1166.7

In Figure 13, the results of the parameter variation are presented for all three scenarios. The adsorption cooling scenario is also evaluated only for the adsorbent Silica Gel SG123.

As observed in previous parameter variations, self-sufficiency increases with the total area of both elements r_{tot} . For all scenarios investigated, a decrease in the self-sufficiency ratio is observed with a decreasing AV ratio, or an increasing edge length of the square storey. More total area r_{tot} is required to achieve the same self-sufficiency level. Generally, the self-sufficiency level increases more strongly with the total area r_{tot} for the 2ACE scenario than for the two photovoltaic scenarios. Therefore, less area is required for the same self-sufficiency level. Furthermore, the 2ACE scenario is limited and the 2PVB scenario again achieves complete self-sufficiency $SL = 100\%$.

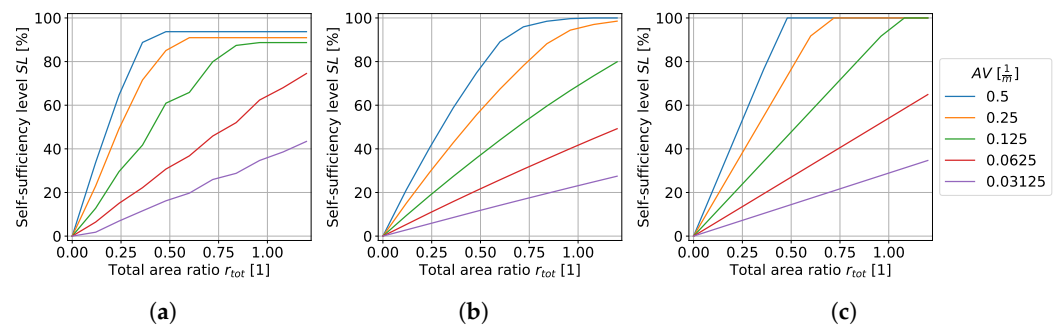


Figure 13. Self-sufficiency level for all scenarios for different façade area-to-room volume ratios AV and total element area r_{tot} . (a) 2ACE scenario. (b) 2PV scenario. (c) 2PVB scenario.

4. Discussion

The results in Figure 7a,b show that Silica Gel SG123 is significantly more suitable for the novel concept 2ACE than Zeolite 13X. This confirms the findings of the study [17]. Specifically, with the same total area, using Silica Gel SG123 achieves near double the self-sufficiency level compared to Zeolite 13X. In other words, achieving the same self-sufficiency level requires approximately twice the area when using Zeolite 13X. Therefore, hypothesis H2 is confirmed by the present results.

The results in Figure 7a,b also serve to assess hypothesis H1. For this purpose, the balance ratio r_{bal} was introduced to examine purely distributing the total area to the east or west element, as represented by the 1ACE concept, and balancing between both sides. The results do not confirm hypothesis H1. Neither solely allocating the total area to the west or east adsorbent, nor distributing it between both sides, leads to a maximum self-sufficiency level. This also indicates that the area focus of the solar cooling elements does not play a decisive role, contradicting the results of the previous study [12], which found that the orientation of the adsorption cooling element strongly influences self-sufficiency. However, the present study used a control concept based on dynamic optimisation, which presumably offers significantly increased flexibility and reliability when dealing with various system parameters, such as element alignment.

The highly fluctuating initial relative loadings in Figure 8a,b highlight the issue of convergence assurance within the 2ACE scenario. No clear, consistent trend is discernible. Once the maximum self-sufficiency level is reached, multiple solutions for the initial conditions should consistently be found. The presence of multiple initial conditions below this maximum is likely due to insufficient iterations during optimisation. It is hypothesised that the objective function exhibits a very flat optimum.

The results in Table 1 offer further insights into the challenges surrounding convergence assurance. Reducing the time step Δt increases the number of system variables. As model complexity increases, computation time t_{ils} rises and the convergence rate $n_{success}$ decreases. This could be addressed by increasing the number of trials in the initial loading study or raising the maximum number of iterations, although this would further increase computation time.

The heat transfer from the collector to the adsorbent is crucial for achieving the temperatures required for desorption, cf. Figure 9. Reducing this from the standard value, cf. Table A5, results in a significant decrease in self-sufficiency once the critical heat transfer coefficient falls below $\frac{G_{cas,a}}{A_{sce}} = 10 \text{ W m}^{-2} \text{ K}$. Considering the measured thermal conductance reported in the thesis (Table 5.17, [21]), relative to the inner surface area of the adsorber tube, yields an experimentally determined heat transfer coefficient of $\frac{G}{A} = 1500 \text{ W m}^{-2} \text{ K}$. Accordingly, it should be feasible to implement a heat transfer design such that heat transfer from the collector to the adsorbent is not a limiting factor.

Hypothesis H3 is not confirmed. Replacing the adsorption cooling elements with PV elements results in a significantly lower self-sufficiency level, assuming Silica Gel SG123 is used, at least up to a total area ratio of $r_{tot} \approx 0.84$. But, the results in Figure 10a also show that the self-sufficiency of the photovoltaic scenario then continues to increase, while the adsorption cooling scenario stagnates. This is because adsorption cooling can only provide cooling energy and not electrical power for the decentralised ventilation system. In other words, this share of electrical energy consumption cannot be independently compensated for in the adsorption cooling scenario. However, if it is assumed that the conversion efficiency of electrical energy into cooling energy eer is lower due to the high ambient temperature on the hottest day of the year, the adsorption cooling scenario is more self-sufficient than the PV scenario, as shown in Figure 12a,b. Therefore, the adsorption cooling scenario appears more resilient.

Compared to the adsorption cooling scenario, the 2PV scenario, cf. Figure 10a, demonstrates a greater self-sufficiency for a balanced area distribution than for one element solely oriented in a single direction. Consistent with Figure 6b, which illustrates cooling power demand, slightly increased cooling capacity is required in the afternoon. Consequently, prioritising area allocation to the west element yields marginally improved self-sufficiency, as demand and cold production are brought closer together. The addition of a small chilled water storage facility could alter this outcome.

Incorporating a battery into the photovoltaic scenario results in a decoupling of power production and cooling energy consumption. The results in Figure 10b reveal not only a significant increase in self-sufficiency, with the maximum shifting towards an eastern emphasis at constant r_{tot} , but also that complete self-sufficiency is achieved from an area ratio $r_{tot} > 0.6$. The eastward shift likely stems from the greater electricity generation potential in that direction. This also holds true when a lower energy efficiency ratio $eer < 2.5$ is assumed, as shown in Figure 12c. To achieve a comparable self-sufficiency level to the adsorption cooling scenario for small total areas $r_{tot} < 0.5$, the 2PVB scenario requires an energy efficiency ratio not falling below $eer < 3$.

The results in Figure 11a show that solely allocating the PV area to the east adsorbent $r_{bal} = 1$ leads to a lower initial state of charge $SOC(0)$. This is because electricity is generated by the east element in the morning and then depleted as the cooling demand rises. The battery capacity profile is reversed for a purely western allocation, as the battery is first discharged with the onset of cooling performance and then recharged by the west-oriented PV element.

The results in Figure 11b should be considered in detail, distinguishing between results with and without complete self-sufficiency $SL = 100\%$. If complete self-sufficiency is not achieved $r_{tot} < 0.72$, the maximum battery capacity is minimal for a balance ratio $r_{bal} \in [0.2, 0.3]$. The eastern PV element should be small and, together with an increased initial capacity, cover the morning cooling demand. The western element then replenishes the energy storage in the afternoon. With complete self-sufficiency for $r_{tot} > 0.72$, it must be assumed that too much electricity is stored in the battery, increasing the maximum capacity. To meet the periodic boundary condition, this excessive storage is discharged at the end of the day by over-conditioning the room, leading to a slight drop in maximum battery capacity after $r_{tot} > 0.72$ and then a sharp increase. However, if feeding into the power grid is permitted but not remunerated, the maximum battery capacity could be reduced, and a capacity lower than the saddle point of approximately $SOC_{max} \approx 6 \text{ kWh}$ could suffice.

The assessment of hypothesis H5 is made with the results in Figure 13. Generally, energy demand increases with a decreasing AV ratio, specifically an increased ratio of floor area to façade area. The heat sources are determined by the façade area, resulting in solar thermal and convective heat gains, and also by the floor area, including heat input from

ventilation and internal gains. However, the heat sinks are solely related to the façade area. With a decreasing AV ratio, the relationship between façade-related heat sinks and floor area-related heat sources changes. The façade-related heat sources are no longer sufficient, resulting in increased electricity consumption from the grid for compression cooling, thus reducing the self-sufficiency level with a decreasing AV ratio. Therefore, regardless of the scenario, slender buildings $AV < 0.25$ can be operated more autonomously than broad or deep buildings. Hypothesis H5 is thus confirmed, consistent with the results of the study (Figure 2, [13]).

Limitations and Future Work

Various measures were taken in this study to ensure the convergence of the dynamic optimisation of the 2ACE scenario, cf. Section 2.2.6. Repeating dynamic optimisation fifty times leads to a significant increase in the calculation time for each data point. Future work should therefore focus on the convergence rate of the dynamic optimisation of the adsorption cooling scenario. This could be achieved, firstly, by using different solvers. In the current study, both valve positions are mapped as system inputs. One possibility would be to solve the valve positions as integer variables in the dynamic optimisation via a mixed-integer nonlinear program (MINLP) solver. However, this is currently not possible with Modelon Impact. Another possibility could be to reduce the number of system inputs and constraints by, for example, implementing the valves as self-regulating flap valves. This would eliminate two inputs and two constraints per adsorption cooling element. However, the problem of continuous differentiability of all sub-models caused by flap valves would need to be resolved.

The time step has a direct influence on the number of optimisation variables in the dynamic optimisation problem. Increasing it results in greater flexibility in utilising the potential of the adsorption cooling elements. Therefore, future work should also focus on reducing the time step, which should directly impact the self-sufficiency level.

So far, only one day, the hottest day of the year, has been considered. If the simulation time can be reduced, different prediction horizons deviating from 24 h should be considered. This could lead to shifts in the timing of electricity generation and cooling energy consumption, and thus to optimal solar cooling element area allocation, as cloud cover and angles of incidence change. In addition, a model predictive control concept should be derived using this dynamic optimisation and applied to an entire summer or year.

To ensure an even more accurate comparison between the data points, all initial ones should correspond to the final state values, as implemented in the dissertation [20]. Due to the challenging convergence of the dynamic optimisations, periodic boundary conditions were not implemented for all states but only for the adsorbent loading and battery capacity. Future studies should investigate this aspect further.

In this study, the working pair Zeolite 13X-water and Silica Gel SG123-water were implemented. Future work should investigate the suitability of other working pairs for this façade-integrated adsorption cooling concept. Furthermore, the heat transfer from the collector surface to the adsorbent should be investigated in greater detail.

System models were developed and used for dynamic optimisation in this study. Future work should simultaneously optimise static design parameters and dynamic inputs. This could be done, for example, with the objective of a holistic life cycle assessment combining grey and operational emissions over a defined life cycle period. This may offer advantages over the photovoltaic plus battery scenario, as the adsorption cooling element does not require rare-earth materials. In addition, the availability and recyclability of raw materials should also be included in the decision-making process.

The photovoltaic scenarios present several advantages over the adsorption cooling scenarios. Firstly, complete self-sufficiency can be achieved when coupled with a battery. Secondly, conversion to electrical energy removes the requirement for on-façade localisation of storage and cooling production. The battery for the 2PVB concept could be centralised for a building, reducing costs and maintenance efforts. Cold production could be implemented on a floor-by-floor basis, in conjunction with decentralised ventilation.

5. Conclusions

In this study, various concepts for façade-integrated solar cooling were presented and optimally operated using dynamic optimisation for the hottest day of the year at the considered location.

In the first step, the system models of all considered scenarios are presented. These are the reference scenario without solar cooling elements, the adsorption cooling scenario with two adsorption cooling elements, the photovoltaic scenario with two photovoltaic elements, and the photovoltaic plus battery scenario. For each scenario, the underlying system equations and the dynamic optimisation problem were presented. This includes the description of the objective function, states, inputs, initial conditions, and constraints.

In the results section, the influence of the adsorbent and system parameters on the self-sufficiency level is investigated. These system parameters include the balance ratio r_{bal} , which determines the area focus between the west and east sides of the two solar cooling elements; the total area ratio r_{tot} , which determines the cooling capacity; the energy efficiency ratio eer of a supporting compression chiller; and the façade area-to-room volume ratio AV , which represents the slenderness of the building type.

The results show that the adsorbent Silica Gel SG123 is significantly better suited for the present application than Zeolite 13X. By using Silica Gel SG123, the same self-sufficiency level can be provided with half the area of all solar cooling elements.

As in previous studies, the ability to provide off-grid cooling increases strongly with the total area of the solar cooling elements r_{tot} . However, no pronounced optimal area balance between the east and west adsorbers is observed. This is likely due to the flexibility enabled by the control concept of dynamic optimisation.

Compared to the scenario with solely compression cooling and two photovoltaic elements, a significantly lower self-sufficiency level is observed. Adding a battery to the photovoltaic scenario not only significantly increases the self-sufficiency level but also enables complete self-sufficiency with electrical energy.

Up to a total area ratio of $r_{tot} = 0.5$, the adsorption cooling scenario usually leads to a higher self-sufficiency than the photovoltaic scenarios. But, the adsorption cooling potential is limited in its ability to provide itself with cooling, as the electrical energy required to operate the ventilation cannot be provided off-grid. This is where the photovoltaic scenarios have a decisive advantage. They produce electrical energy which can be used to operate the ventilation and provide cooling.

For slender buildings with a high AV ratio, relatively less façade area is required for solar cooling elements than for broad buildings with a low AV ratio. This is because the floor area increases more strongly than the façade areas, whereby the heat sources exceed the façade area-related heat sinks.

The main limitations of the adsorption cooling scenario remain its convergence rate. The initial loading study introduced is very time-consuming and should be replaced by a coupled optimisation of dynamic and static system variables. Subsequently, prediction horizon lengths should be analysed and model predictive control concepts should be derived and examined over a period of months of operation.

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Data Availability Statement: The full Python and Modelica source code as well as the data underlying the result figures are publicly available under the data repository of the University of Stuttgart: <https://doi.org/10.18419/DARUS-5666>.

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Nomenclature

The following abbreviations and symbols are used in this manuscript:

1ACE	concept with one adsorber, condenser, and evaporator
2A1CE	concept with two adsorbers and one condenser and evaporator
2ACE	concept with two compact elements, each with one adsorber, condenser, and evaporator
2PV	concept with compression cooling and two photovoltaic elements
2PVB	concept with compression cooling and two photovoltaic elements plus one battery
CRC1244	Collaborative Research Center 1244 at the University of Stuttgart
EHF	external heat flux
H_i	Hypotheses i
VLE	vapour–liquid equilibrium

Variables:

Symbol	Description	Unit
A	area	m^2
acr	air change rate	h^{-1}
AV	façade area-to-room volume ratio $AV = \frac{4bh}{b^2h} = \frac{4}{b}$	m^{-1}
b, h	edge length, height of the square room geometry	m
β_{LDF}	intra-particle mass transfer coefficient	s^{-1}
c	specific heat capacity	$\text{J kg}^{-1} \text{K}$
C	heat capacity	J K^{-1}
cop, eer	coefficient of performance, energy efficiency ratio	1
D_{eff}	effective diffusion coefficient	$\text{m}^2 \text{s}^{-1}$
d_{sph}	diameter of the adsorbent grain	m
E	total daily electrical energy consumption of the scenario	kWh
G	heat conductance	W K^{-1}
h	heat transfer coefficient	$\text{W m}^{-2} \text{K}$
I	irradiance	W m^{-2}
λ	heat conduction coefficient	$\text{W m}^{-1} \text{K}$
occ	occupancy signal	1
p	pressure	Pa
$P, \dot{Q}$	electrical, thermal power	W
$\dot{q}$	specific heat flow	W m^{-2}

r	area ratio, i.e., $r_{win} = \frac{A_{win}}{bh}$	1
ρ	density	$\text{m}^3 \text{kg}^{-1}$
SOC	state of charge	kWh
SL	self-sufficiency level	%
$t, \Delta t$	time, time step width	s
θ	relative water loading	1
T	temperature	$^{\circ}\text{C}$
u	dimensionless input signals	1
vlv	valve signal	1
$\dot{V}$	volume flow	$\text{m}^3 \text{h}^{-1}$
$\dot{x}, x, u, d$	vector of state derivatives, states, inputs, and disturbances	-
f	differential-algebraic system of equations of a scenario	-
$\mathbb{X}, \mathbb{U}$	collection of state and input constraints	-
Subscripts:		
Symbol	Description	
amb, bs	ambient, black sky	
bal, tot	balance, total	
B^{-}	battery discharge capacity	
cas, ins, cav	casing, insulation, cavity	
col, a, c, e	collector, adsorber, condenser, evaporator	
gti	global tilted irradiance	
HP, CH, AHU, PV	signal of the heat pump, compression chiller, air handling unit, photovoltaic	
inf, ven	infiltration, ventilator	
ll, ul	lower or upper limit	
nom	at nominal conditions	
pmp	pump signal	
s1, s2, s3, s4	reference, adsorption cooling, photovoltaic, photovoltaic plus battery scenario	
sha	shading of the collector	
W, E	west, east	
win, ext, int, sce	window, external wall, internal wall, solar cooling element	
z	zone	

Appendix A. General Settings and Material Properties

Appendix A.1. Envelope Properties

The window area is divided into a frame and glazing component. The frame accounts for 8 % of the total window area assigned via the window-to-wall ratio r_{win} . The thermal transmittance of the frame is assumed to be $U_{fra} = 1.7 \frac{\text{W}}{\text{m}^2 \text{K}}$.

The layer composition of the glazing is given in Table A1. This is defined according to the sun protection window “triple low-e argon deflected” in the WINDOW programme [33]. The following relationships apply:

$$\begin{aligned} \tau_{sol,f} = \tau_{sol,b} = \tau_{sol} \quad \tau_{ir,f} = \tau_{ir,b} = \tau_{ir} = 0 \\ \rho = 2510 \text{ kg m}^{-3} \quad c = 720 \text{ J kg}^{-1} \text{ K} \quad \lambda = 1 \text{ W m}^{-1} \text{ K} \end{aligned} \quad (\text{A1})$$

Table A1. Layer build-up and thickness of the glazing from the outside to the inside.

Material	Low-e-1	Air-10-Argon-90	Clear	Air-10-Argon-90	Low-e-2
thickness/[mm]	5.7	12.7	5.7	12.7	5.7

The properties of the gas layers were taken from ISO 52022-3 (Table F.1, [25]), assuming a mixture ratio of 10 % air and 90 % argon. For simplification of the dynamic optimisation,

the Nusselt number was set to 1 for modelling the gas gap. The spectral material properties of the layers are presented in Table A2 and taken from the WINDOW program.

Table A2. Spectral material data of the glazing layers.

Material	τ_{sol} [1]	$\rho_{sol,f}$ [1]	$\rho_{sol,b}$ [1]	ε_f [1]	ε_b [1]
low-e-1	0.362	0.305	0.463	0.84	0.035
low-e-2	0.362	0.463	0.305	0.035	0.84
clear	0.771	0.07	0.07	0.84	0.84

The layer composition of the four external walls is given in Table A3. The ceiling and floor are considered as internal walls, modelled as a 13 cm thick layer of concrete.

Table A3. Layer build-up and thickness of the external walls from the outside to the inside.

Material	Aluminum	Mineral Wool	Aluminum
thickness/[mm]	2	200	2

The material data are presented in Table A4. According to the summer conditions in ISO 52022-3 (Chapter 6.4.6, [25]), the external and internal heat transfer coefficients are set constant for all envelope elements, with $h_{out} = 8 \text{ W m}^{-2} \text{ K}$ and $h_{in} = 2.5 \text{ W m}^{-2} \text{ K}$, respectively.

Table A4. Material data of the external and internal walls.

Material	ρ_{sol} [1]	ε [1]	ρ [$\frac{\text{kg}}{\text{m}^3}$]	c [$\frac{\text{J}}{\text{kgK}}$]	λ [$\frac{\text{W}}{\text{mK}}$]
aluminum	0.9	0.05	2700	900	200
mineral wool	0.6	0.9	24	1030	0.032
concrete	0.5	0.9	2500	1000	2.5

Appendix A.2. Adsorption Cooling Element Properties

Table A5 lists all parameters used in the models of the adsorber, condenser, and evaporator. The ratios $\frac{C_{cas}}{A_{sce}}$ and $\frac{G_{cas}}{A_{sce}}$ are given for an area ratio $r_{sce,i} = 0.6$. They depend on the detailed constructions given in the study [28] and thus change slightly with the element area.

Table A5. Properties of the adsorber, condenser, and evaporator models.

	λ [$\frac{\text{W}}{\text{mK}}$]	ρ [$\frac{\text{kg}}{\text{m}^3}$]	Casing c [$\frac{\text{J}}{\text{kgK}}$]	C/A_{sce} [$\frac{\text{J}}{\text{m}^2\text{K}}$]	G/A_{sce} [$\frac{\text{W}}{\text{m}^2\text{K}}$]	Insulation λ [$\frac{\text{W}}{\text{mK}}$]	G/A_{sce} [$\frac{\text{W}}{\text{m}^2\text{K}}$]
adsorber				26,142	679,457		
condenser	200	2700	900	14,682	267,833	0.003	0.15
evaporator				15,257	278,333		

Table A6 lists all Dubinin–Astakhov parameters for both working pairs, namely, the characteristic energy E_{cha} , the exponent n , and the maximum pore volume filling W_{max} . The Dubinin–Astakhov parameters for Zeolite 13X apply to adsorption enthalpies smaller than 500 kJ kg^{-1} and for Silica Gel SG123 smaller than 200 kJ kg^{-1} .

Table A6. Parameter of the Dubinin–Astakhov equation as well as the material parameters of both working pairs.

	E_{cha} [$\frac{kJ}{kg}$]	n [—]	W_{max} [$\frac{cm^3}{g}$]	ρ_{bulk} [$\frac{kg}{m^3}$]	c [$\frac{J}{kgK}$]	d_{sph} [mm]	$D_{eff,ads}$ [$\frac{m^2}{s}$]	$D_{eff,des}$ [$\frac{m^2}{s}$]
Zeolite 13X	1608.69	1.110	0.29618	582	960	1.4	3.4×10^{-10}	2.8×10^{-9}
Silica Gel SG123	193.90	1.921	0.41178	710	1000	0.9	1.8×10^{-10}	

Appendix A.3. PV Panel

Table A7 lists all relevant parameters of the PV model. The data were taken from the datasheet of the “SOLARWATT Panel vision GM 3.0 construct” module. A derating factor of $\eta_{PV} = 1$ was assumed.

Table A7. Properties of the PV modules.

$P_{rate_PV/A}$ [$\frac{W}{m^2}$]	η_{PV} [1]	α_{TP} [%/K]	T_{NOCT} [°C]	η_{STC} [1]	T_{STC} [°C]	$I_{gti,STC}$ [$\frac{W}{m^2}$]
194.92	1	−0.34	44	0.196	25	1000

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