



# Design, Modeling, and Optimization of a Dual-Season Solar Chimney for Energy Consumption and Carbon Emission Reduction: A Case Study in Tehran

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| ARTICLE INFO                                                                                                                                                                                             | ABSTRACT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
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| <p>Article History:</p> <p>Received 5 October 2025</p> <p>Received in revised form 26 December 2025</p> <p>Accepted 20 January 2026</p> <p>Available online 4 March 2026</p>                             | <p>Passive solar systems can reduce the energy use of buildings. This study evaluates a segmented vertical solar chimney integrated into an eight-storey residential building (2,176 m<sup>2</sup>) in Tehran, a cold semi-arid climate, for both seasons: in winter it preheats incoming air, and in summer it exhausts warm indoor air by thermal buoyancy. A DesignBuilder (EnergyPlus) model calibrated against utility bills was used to compare three chimney geometries and five vent arrangements. Five design parameters (chimney depth, height, glazing type, insulation thickness and absorber thickness) were then evaluated at three levels each with a Taguchi L18 array, using signal-to-noise ratios and ANOVA. Across the 18 configurations, the chimney reduced annual heating energy by 2.4–4.0% (4.28–7.14 MWh), cooling energy by 1.5–2.6% (0.40–0.69 MWh) and CO<sub>2</sub> emissions by 1.17–1.59 t. Chimney depth was the dominant parameter for every objective (65–80% contribution; <math>p &lt; 0.001</math>), but heating and cooling favoured opposite levels: 0.3 m for heating and 0.5 m for cooling. Because heating dominates the annual balance, the configuration selected was a 0.3 m depth, H+1.2 m height, 0.5 cm absorber, 8 cm insulation and double glazing. For this configuration the Taguchi model predicts a heating reduction of 4.2% (<math>7.55 \pm 0.23</math> MWh) and a CO<sub>2</sub> reduction of 1.60 t per year. These savings are modest relative to the uncertainty of the building model and should be weighed against the chimney's embodied carbon.</p> |
| <p>Keywords:</p> <p>Segmented solar chimney;</p> <p>Dual-season operation;</p> <p>Building energy simulation;</p> <p>Taguchi method; Analysis of variance (ANOVA); CO<sub>2</sub> emission reduction</p> |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |

## 1. INTRODUCTION

Buildings account for a large share of final energy use and greenhouse-gas emissions worldwide, and the residential sector in Iran is no exception: space heating, which is supplied mainly by natural gas, and space cooling, which is supplied mainly by electricity, dominate household energy use in Tehran. Reducing these loads through

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passive design, without additional operational energy, is therefore an attractive route to both lower energy bills and lower emissions [1, 2].

The solar chimney is one of the most studied passive strategies for this purpose. It consists of a vertical or inclined channel formed by a glazed cover and an absorber wall; solar radiation transmitted through the glazing heats the absorber, the absorber heats the air in the channel, and the resulting density difference drives an upward airflow by thermal buoyancy (Fig. 1) [1, 3]. Unlike wind-driven ventilation, the airflow is available on calm days and is strongest when solar gains, and hence cooling needs, are highest. Depending on how the inlets and outlets are arranged, the same device can operate in two modes: in summer it extracts warm indoor air and induces cross-ventilation, and in winter it preheats outdoor air (or recirculates room air) before it enters the occupied space, in a way similar to a Trombe wall [2, 4].

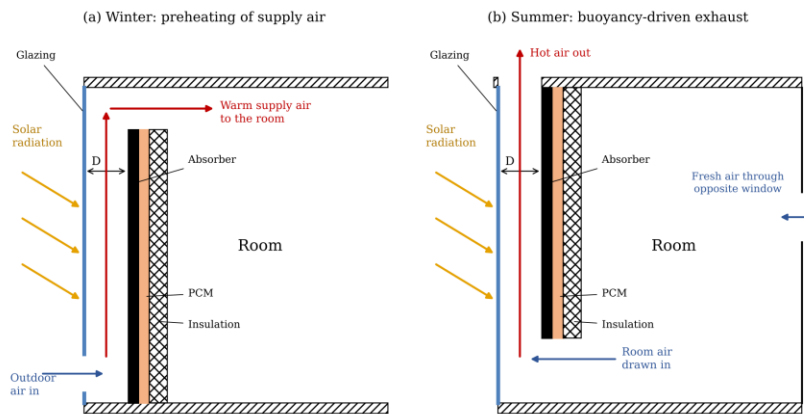


**Fig. 1.** Schematic of a solar chimney module: (a) winter operation, in which outdoor air is preheated in the channel and supplied to the room; (b) summer operation, in which room air is exhausted by thermal buoyancy and fresh air enters through the opposite window (drawn by the authors after [1–3]).

The performance of a solar chimney depends on its geometry (height, depth of the air gap, width, inlet and outlet areas), on the optical and thermal properties of its materials (glazing transmittance and U-value, absorber absorptance and thermal mass, insulation behind the absorber), on how it is integrated into the building, and on the local climate [1, 2]. Many of these parameters interact, and their best values differ between the heating and the cooling season. For a building in a climate with both a significant heating and a significant cooling season, such as Tehran, the design problem is therefore genuinely multi-objective. Most previous studies have examined single-storey buildings, laboratory-scale test rigs or a single operating mode, and few have quantified how the design parameters rank when the chimney is integrated into a real multi-storey residential building and evaluated over a whole year [5, 6].

This study addresses that gap. A segmented solar chimney, in which each floor is served by its own chimney modules, is designed for an existing eight-storey residential building in Tehran and evaluated with a calibrated whole-building energy model. The objectives are (i) to identify a suitable chimney geometry and vent arrangement for dual-season operation, (ii) to quantify the influence of five design parameters on heating energy, cooling energy, total site energy and CO<sub>2</sub> emissions using a Taguchi orthogonal array and ANOVA, and (iii) to estimate the energy and emission savings that an optimised chimney can achieve, together with the uncertainty of these estimates.

The main contributions are:

1. a whole-building, whole-year assessment of a segmented dual-season solar chimney in a multi-storey residential building in a cold semi-arid climate;
2. a screening of three chimney geometries and five vent arrangements, showing that the geometry, rather than the vent arrangement, decides whether the chimney saves or costs heating energy;

3. a complete statistical analysis of a five-factor L18 Taguchi experiment (main effects, signal-to-noise ratios, ANOVA with p-values and pure contributions, additive-model predictions with confidence intervals) for four objectives; and
4. a discussion of the trade-off between heating and cooling objectives, of the magnitude of the savings relative to model uncertainty, and of the embodied-carbon balance of the device.

The remainder of the paper is organised as follows. Section 2 reviews previous work; Section 3 describes the methodology, including model validation, the case-study building, the chimney design and the statistical framework; Section 4 presents the results; Section 5 discusses them together with the limitations of the study; and Section 6 concludes.

## **2. LITERATURE REVIEW**

### **2.1. Principles and modelling of solar chimneys**

Solar chimneys have been studied for more than three decades. Bansal et al. [7] developed one of the first mathematical models of a solar chimney combined with a wind tower and showed its potential to induce natural ventilation in buildings. Afonso and Oliveira [8] compared simulations and measurements of a chimney integrated into a building and showed that a solar chimney can increase the ventilation rate considerably compared with a conventional chimney. Ong [9] proposed a steady-state thermal-network model of the glazing, air channel and absorber that has since been used and extended in many studies. Khedari et al. [10] tested solar chimneys in an air-conditioned building in the field and reported a reduction of the cooling load, and Chen et al. [11] investigated experimentally the effect of gap width, height and inclination with a uniformly heated wall. Comprehensive reviews of the applications of solar chimneys and of solar-chimney-integrated systems for heating and cooling are given by Zhai et al. [2] and Monghasemi and Vadiiee [4]; Shi et al. [1] reviewed the factors that determine their performance in buildings, and Saadatian et al. [12] reviewed Trombe walls, which share the same physics in heating mode.

### **2.2. Design parameters**

Previous studies agree that the performance of a solar chimney is strongly influenced by geometry, material properties, installation and climate [1, 2]. Chimney height is one of the most influential geometric variables: a taller chimney increases the stack height and hence the buoyancy pressure and the air velocity [13]. The depth (air-gap width) of the channel has an optimum: too narrow a gap increases friction, too wide a gap allows reverse flow and a cold core of air, and an optimum of about 0.2–0.3 m has frequently been reported for building-scale chimneys [2, 11]. The glazing determines how much solar radiation reaches the absorber and how much heat is lost from the channel; double glazing generally increases the thermal efficiency of the chimney by reducing these losses [2, 4]. Absorber properties and insulation behind the absorber control the heat transferred to the air and to the room. Inclination, solar irradiance and ambient wind speed also affect the flow [14]. Hosein and Selim [3] examined the effect of geometrical and operational parameters and of alternative cover materials on a chimney for natural ventilation, and Moosavi et al. [15] measured the cooling performance of solar-assisted natural ventilation in a large building in a warm and humid climate.

### **2.3. Optimisation and whole-building assessment**

Because the parameters interact and the objectives conflict, optimisation methods are increasingly used. Abdeen et al. [6] combined experiments and simulation to optimise a solar chimney for thermal comfort in Egypt. Taguchi orthogonal arrays are attractive for building-simulation studies because they allow the main effects of many parameters to be estimated from a small number of simulations [16, 17], and they have been used together with ANOVA to rank the parameters of passive and active building systems. Annual whole-building simulations of solar chimneys, as in Hong et al. [5], show that the savings achievable in a real building depend strongly on the climate and on how the chimney is coupled to the HVAC system.

## 2.4. Research gap

Most of the existing literature has focused on laboratory-scale models, single-storey buildings or a single operating mode. The application of solar chimneys to multi-storey residential buildings under actual climatic conditions remains insufficiently explored, in particular for Tehran, where both heating and cooling loads are significant. The dual heating–cooling operation of such systems, and the question whether the same design can serve both seasons, have also received limited attention. The present study addresses these gaps for a segmented, dual-season chimney in an existing eight-storey building in Tehran.

## 3. METHODOLOGY

This study combines whole-building energy simulation (BES) with a statistical design of experiments. The work was carried out in five stages:

1. Validation of the simulation approach against a published reference case of a building with a solar chimney (Section 3.1).
2. Modelling and calibration of the case-study building in Tehran against measured utility data (Section 3.2).
3. **Screening of chimney geometries and vent arrangements:** three geometries with equal internal air volume and five inlet–outlet vent arrangements were simulated, and the best combination was retained (Section 3.3).
4. **Taguchi experiment:** five design parameters at three levels were varied according to an L18 orthogonal array, and the 18 configurations were simulated (Section 3.4).
5. **Statistical analysis and confirmation:** main effects, signal-to-noise ratios and ANOVA were computed for four objectives, the optimal levels were identified, the additive model was used to predict the performance of the selected design, and this design was simulated for confirmation (Sections 3.5 and 4.7).

### 3.1. Validation of the simulation approach

To check that the chimney can be represented adequately in Design Builder, the two-storey residential building with a passive solar chimney in Hangzhou, China, described by Hong et al. [5], was modelled with the geometry, constructions and internal loads reported in that study. The energy use of the ventilation system with and without the chimney and the resulting saving were compared with the published values (Table 1).

**Table 1.** Comparison of the present model with the reference case of Hong et al. [5].

| Quantity                                                              | Reference value<br>[5] | This<br>model | Unit               | Difference                              |
|-----------------------------------------------------------------------|------------------------|---------------|--------------------|-----------------------------------------|
| Energy used by the ventilation system, building without solar chimney | 28.60                  | 28.82         | kWh/m <sup>2</sup> | +0.8%                                   |
| Energy used by the ventilation system, building with solar chimney    | 26.02                  | 25.93         | kWh/m <sup>2</sup> | −0.3%                                   |
| Energy saving due to the solar chimney                                | 9.0                    | 10.0          | %                  | +1.0 percentage point<br>(11% relative) |

The absolute energy use agrees within 1%. The saving attributable to the chimney, which is the quantity of interest here, differs by one percentage point, i.e. by about 11% in relative terms. It should be noted that the reference values are themselves the output of a simulation study and not measurements, so this comparison verifies that the modelling approach reproduces an independent model; it is not an experimental validation.

### 3.2. Case-study building and calibration

The case-study building is an eight-storey residential building (two basement levels and six residential floors) with a total floor area of 2,176 m<sup>2</sup>, located in Saadat Abad, Tehran (cold semi-arid climate, Köppen BSk). Each residential floor contains two units (east and west). The typical floor plan and the modelled façade are shown in Fig. 2.

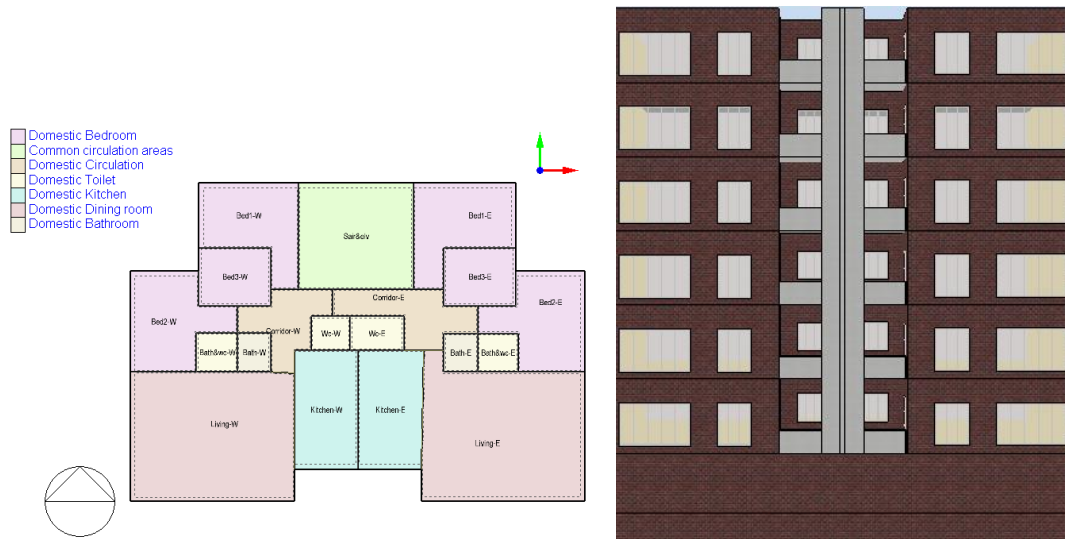


**Fig. 2.** Typical floor plan and modelled façade of the eight-storey residential case-study building in Saadat Abad, Tehran.

The windows are double glazed with a thermal transmittance of 1.761 W/m<sup>2</sup>K. The external walls are a composite of autoclaved aerated concrete (Hebel) blocks and a brick façade, a typical construction in Tehran. Heating is supplied by gas-fired equipment and cooling by electric equipment.

The model was calibrated against the monthly gas and electricity bills of the west unit on the first floor for 2023 (Table 2). Following ASHRAE Guideline 14 [18], a model is considered calibrated with monthly data when the normalized mean bias error (NMBE) is within  $\pm 5\%$  and the coefficient of variation of the root-mean-square error, CV(RMSE), is below 15%. After adjusting the infiltration rate, the occupancy schedules and the heating set-point, the calibrated model gave NMBE = 3.6% and CV(RMSE) = 10.3% for gas, and NMBE = -3.4% and CV(RMSE) = 10.1% for electricity, so both criteria are met. Because all twelve units share the same constructions, systems and schedules, the calibrated input parameters were applied unchanged to the whole-building model; the whole-building gas and electricity totals differ from the sum of the 2023 bills of the twelve units by 4.6% and 3.9%, respectively. With the calibrated model, the annual heating and cooling energy of the whole building in the base case (without chimney) are 180.24 MWh (gas) and 26.20 MWh (electricity); total gas use, including domestic hot water and cooking, is 251.58 MWh and total electricity use is 49.73 MWh (Fig. 5).

**Table 2.** Monthly calibration of the west unit on the first floor (utility bills of 2023 versus calibrated model).

| Month | Gas, measured (kWh) | Gas, simulated (kWh) | Electricity, measured (kWh) | Electricity, simulated (kWh) |
|-------|---------------------|----------------------|-----------------------------|------------------------------|
| Jan   | 3,950               | 3,600                | 270                         | 277                          |
| Feb   | 3,420               | 3,490                | 250                         | 283                          |
| Mar   | 2,560               | 2,710                | 255                         | 277                          |
| Apr   | 1,310               | 1,390                | 270                         | 294                          |
| May   | 720                 | 810                  | 330                         | 353                          |
| Jun   | 560                 | 520                  | 480                         | 493                          |
| Jul   | 540                 | 550                  | 610                         | 544                          |
| Aug   | 550                 | 510                  | 620                         | 695                          |
| Sep   | 600                 | 500                  | 470                         | 433                          |

|                 |        |              |       |               |
|-----------------|--------|--------------|-------|---------------|
| Oct             | 1,150  | 1,040        | 300   | 318           |
| Nov             | 2,380  | 2,330        | 255   | 263           |
| Dec             | 3,540  | 3,120        | 275   | 290           |
| Annual          | 21,280 | 20,570       | 4,385 | 4,520         |
| NMBE / CV(RMSE) | —      | 3.6% / 10.3% | —     | -3.4% / 10.1% |

### 3.3. Solar chimney design

**Geometries.** Three chimney geometries with the same internal air volume were compared (Fig. 3): a reference geometry derived from previous studies (Geometry 2), in which a continuous chimney runs over the height of the façade (Fig. 3, middle), and two segmented geometries in which every floor is served by its own chimney system. In Geometry 1 each floor has one chimney two storeys high; in Geometry 3 each floor has two separate single-storey chimney modules (2.05 m high, 1.05 m wide and 0.3 m deep in the base design; Fig. 4).

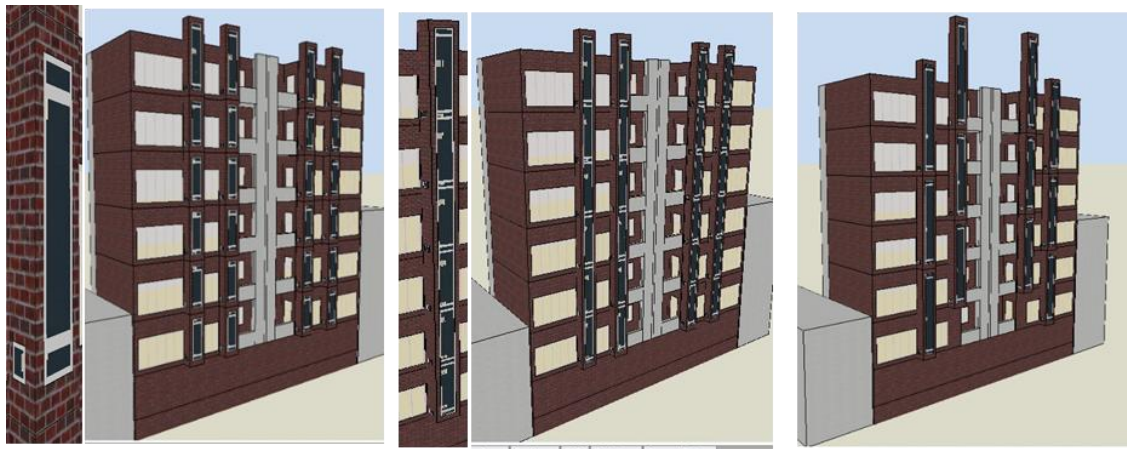


**Fig. 3.** Solar chimney geometries (from right to left: Geometry 1, Geometry 2 and Geometry 3).

**Vent arrangements.** Five inlet–outlet arrangements with standard opening dimensions were examined (Table 3). To avoid confusion with the geometries, they are called vent arrangements V1–V5 in this paper.

**Table 3.** Inlet–outlet vent arrangements.

| Arrangement | Description                                                             |
|-------------|-------------------------------------------------------------------------|
| V1          | Inlets on the south and west sides; outlets on the south and east sides |
| V2          | Inlet and outlet vents on the south side only                           |
| V3          | Outlet vent on the south side only                                      |
| V4          | Outlet vents on the south, east and west sides                          |
| V5          | Inlets on the south and west sides; outlet on the south side            |

**Materials and operating modes.** The chimney consists of an external glazing, an air channel, a black metal absorber, a layer of phase-change material (PCM, RT35) and polyurethane insulation towards the room. In winter (Fig. 4, right), outdoor air enters at the lower opening, is heated in the channel and is supplied to the room through the upper opening. In spring and summer (Fig. 4, left), room air enters the chimney at the lower opening and is exhausted to the outside at the top, which draws fresh air into the dwelling through the windows on the opposite façade.

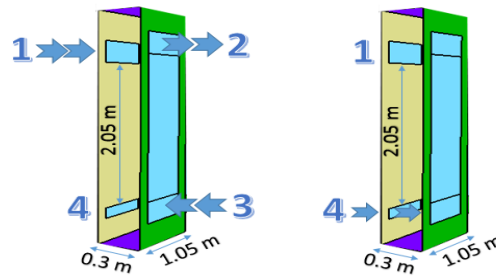


**Fig. 4.** Seasonal operating modes of a chimney module (from right to left: winter mode, spring/summer mode).

**Representation in the simulation model.** Each chimney module was modelled as a separate thermal zone bounded by the glazing and the absorber assembly. Air exchange between the outdoor environment, the chimney zones and the rooms was calculated with the EnergyPlus Airflow Network, because the simpler solar-chimney object of EnergyPlus represents exhaust operation only and cannot represent winter preheating of supply air [19]. Every vent was represented as a detailed opening with a discharge coefficient of 0.65 and the opening areas of the vent arrangement under study. The vents were controlled by seasonal schedules: in winter mode (15 November–15 March) the lower outdoor opening and the upper room-side opening were open whenever the channel air was warmer than the room air, and in spring/summer mode (rest of the year) the lower room-side opening and the upper outdoor opening were open whenever the channel air was warmer than the room air and the outdoor air was below 30 °C. The PCM layer (RT35; melting range 29–36 °C; latent heat 160 kJ/kg; 2 cm) was modelled with the conduction finite-difference algorithm and the manufacturer’s enthalpy–temperature curve. The absorber is a black-painted steel plate (solar absorptance 0.95, thermal emittance 0.90) whose thickness is varied in Table 4, and the polyurethane insulation is placed between the PCM layer and the room. In Table 4,  $H$  denotes the 2.05 m height of the glazed collector of the base module, so the three height levels correspond to total chimney heights of 3.25, 4.25 and 5.25 m measured from the lower opening to the outlet; the part above the collector is an opaque, insulated stack. Airflow rates and channel air temperatures for representative winter and summer days are reported in Section 4.8.

### 3.4. Taguchi experimental design

Five design parameters, each at three levels, were selected for the optimisation (Table 4). A full factorial design would require  $3^5 = 243$  simulations; the Taguchi L18 orthogonal array reduces this to 18 while allowing all main effects to be estimated [16, 17]. The five three-level factors were assigned to five of the seven three-level columns of the L18 array (Table 6). It was verified that every pair of factors forms a balanced design in which each of the nine level combinations occurs exactly twice. Each factor has 2 degrees of freedom, so the five factors use 10 of the 17 available degrees of freedom and 8 remain for the error term.

**Table 4.** Design parameters and levels.

| Parameter               | Level 1   | Level 2   | Level 3   | Unit |
|-------------------------|-----------|-----------|-----------|------|
| Chimney depth (air gap) | 0.3       | 0.4       | 0.5       | m    |
| Chimney height          | $H + 1.2$ | $H + 2.2$ | $H + 3.2$ | m    |
| Glazing type            | single    | double    | triple    | –    |
| Insulation thickness    | 8         | 9         | 10        | cm   |
| Absorber thickness      | 0.5       | 1.0       | 1.5       | cm   |

**Objectives.** Four responses were computed for each configuration relative to the base building without chimney: the reduction of annual heating energy (gas), the reduction of annual cooling energy (electricity), the reduction of total site energy (heating plus cooling, in kWh), and the reduction of annual CO<sub>2</sub> emissions. The total site energy adds gas and electricity in kWh and is reported for comparison with previous studies; because the two carriers have

different primary-energy and emission factors, the CO<sub>2</sub> objective is the physically more meaningful combined indicator.

**CO<sub>2</sub> emissions.** CO<sub>2</sub> emissions were computed from the total gas and electricity consumption of the building with constant emission factors. Fitting the reported emission reductions of the 18 configurations to the changes in gas and electricity use gives factors of 0.188 kg CO<sub>2</sub>/kWh for natural gas and 0.606 kg CO<sub>2</sub>/kWh for electricity (maximum residual 3 kg), and these factors reproduce the base-case emissions within 0.2%.

### 3.5. Statistical analysis

For each objective  $y$  (to be maximised), the analysis comprised the following steps.

**Main effects.** The mean response at level  $l$  of factor  $j$  is  $\bar{y}_{jl} = \frac{1}{6} \sum_{i: x_{ij}=l} y_i$ , since each level occurs in 6 of the 18 runs. The difference between the largest and smallest level mean ( $\Delta$ ) measures the size of the effect.

**Signal-to-noise ratio.** For a larger-the-better characteristic, the S/N ratio of a group of runs is

$$\eta = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \text{ dB} \quad (1)$$

In a deterministic simulation without noise factors, the S/N ratio is a monotonic transformation of the response and contains no additional information about robustness; it is reported for completeness, and the conclusions are drawn from the responses themselves.

**ANOVA.** The total sum of squares  $SS_T = \sum_i (y_i - \bar{y})^2$  is decomposed into the factor sums of squares  $SS_j = 6 \sum_{l=1}^3 (\bar{y}_{jl} - \bar{y})^2$  and an error term  $SS_e = SS_T - \sum_j SS_j$  with 7 degrees of freedom. The F-ratio of factor  $j$  is  $F_j = (SS_j/2)/(SS_e/7)$ , and its p-value follows from the  $F(2, 7)$  distribution. The pure percentage contribution [16] is

$$\rho_j = \frac{SS_j - 2 MS_e}{SS_T} \times 100\% \quad (2)$$

Because the simulations are deterministic and not replicated, the error term does not represent random experimental error but the effects not included in the main-effects model, chiefly interactions between factors. The p-values must therefore be read as an indication of which main effects are large compared with these neglected effects.

**Prediction and confirmation.** Under the additive model, the expected response at a combination of levels  $(l_1, \dots, l_5)$  is

$$\hat{y} = \bar{y} + \sum_{j=1}^5 (\bar{y}_{jl_j} - \bar{y}) \quad (3)$$

with a 95% confidence interval  $\pm \sqrt{F_{0.05}(1,7) MS_e / n_{\text{eff}}}$ , where  $n_{\text{eff}} = 18/(1 + 10)$  [16]. Because the optimal combination is generally not one of the 18 runs, it must be simulated in a confirmation run; agreement between the prediction and the confirmation run indicates that interactions are small and that the additive model is adequate.

All analyses were carried out in Qualitek-4 and verified independently with a Python script, which reproduced the contributions computed by Qualitek-4 within  $\pm 0.5$  percentage points; the values in Tables 8 and 9 are those of the independent recalculation.

## 4. RESULTS

### 4.1. Base case

With the calibrated model, the annual heating and cooling energy of the building without solar chimney are 180.24 MWh and 26.20 MWh, i.e. 82.8 and 12.0 kWh per m<sup>2</sup> of floor area. Heating therefore accounts for about 87% of the space-conditioning energy, and any design that is to reduce total energy or emissions substantially must above all reduce the heating demand. The results for the calibrated west unit and for the whole building are shown in Fig. 5.

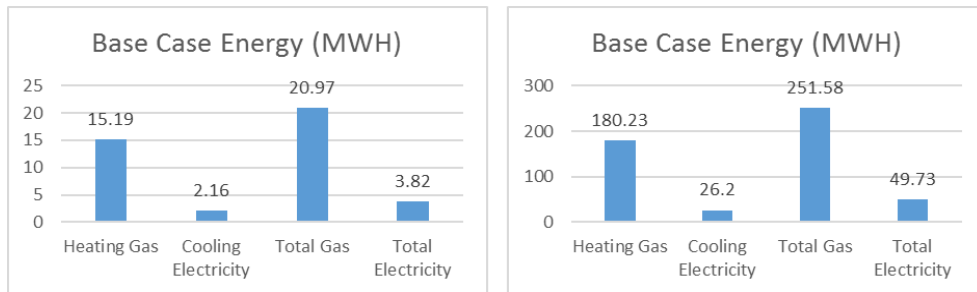


Fig. 5. Base-case annual energy use: (a) west residential unit on the first floor; (b) whole building.

### 4.2. Screening of geometries and vent arrangements

Table 5 summarises the annual savings of the three geometries with the five vent arrangements; negative values denote an increase in energy use.

**Table 5.** Annual energy savings of the three chimney geometries with the five vent arrangements of Table 3 (negative values: increase in consumption).

| Saving (kWh)        | V1     | V2     | V3      | V4      | V5     |
|---------------------|--------|--------|---------|---------|--------|
| Geometry 1, cooling | 593    | 592    | 640     | 640     | 593    |
| Geometry 1, heating | −1,301 | −1,300 | −2,287  | −2,287  | −1,301 |
| Geometry 2, cooling | 232    | 334    | 303     | 303     | 334    |
| Geometry 2, heating | −9,774 | −9,493 | −10,195 | −10,195 | −9,491 |
| Geometry 3, cooling | 467    | 472    | 470     | 470     | 467    |
| Geometry 3, heating | 6,285  | 6,299  | 5,247   | 5,247   | 6,285  |

Two observations are important. First, **the geometry decides the sign of the heating effect**. Geometries 1 and 2 save some cooling energy but increase the heating demand, by 1.3–2.3 MWh for Geometry 1 and by 9.5–10.2 MWh (5.3–5.7% of the base case) for the continuous reference Geometry 2. The probable reason is that a tall continuous channel loses heat to the outside through a large glazed area and, in winter, delivers cold air to the lower floors or extracts warm room air, so that it acts as a heat sink. Only the segmented Geometry 3, with two single-storey modules per floor, saves heating energy (5.2–6.3 MWh). Second, **the vent arrangement has a much smaller influence**, and several arrangements give identical results: V3 and V4 give exactly the same savings for all three geometries, and V1 and V5 give identical savings for Geometries 1 and 3. Since these arrangements differ in the number and orientation of openings, identical annual results suggest that, in the model, the additional openings do not carry any airflow.

Geometry 3 with vent arrangement V2 (inlet and outlet on the south side) gave the largest heating saving, 6,299 kWh (3.5%), together with a cooling saving of 472 kWh (1.8%), and was retained for the parametric study.

### 4.3. Results of the L18 experiment

Table 6 lists the 18 configurations of the L18 array and Table 7 the corresponding simulation results.

**Table 6.** Configurations of the L18 orthogonal array.

| Run | Depth (m) | Height (m) | Absorber thickness (cm) | Insulation thickness (cm) | Glazing type |
|-----|-----------|------------|-------------------------|---------------------------|--------------|
| 1   | 0.3       | H+1.2      | 0.5                     | 8                         | single       |
| 2   | 0.3       | H+2.2      | 1.0                     | 9                         | double       |
| 3   | 0.3       | H+3.2      | 1.5                     | 10                        | triple       |
| 4   | 0.4       | H+1.2      | 1.0                     | 9                         | single       |
| 5   | 0.4       | H+2.2      | 1.5                     | 10                        | double       |
| 6   | 0.4       | H+3.2      | 0.5                     | 8                         | triple       |
| 7   | 0.5       | H+1.2      | 1.5                     | 8                         | double       |
| 8   | 0.5       | H+2.2      | 0.5                     | 9                         | triple       |
| 9   | 0.5       | H+3.2      | 1.0                     | 10                        | single       |
| 10  | 0.3       | H+1.2      | 1.0                     | 10                        | triple       |
| 11  | 0.3       | H+2.2      | 1.5                     | 8                         | single       |
| 12  | 0.3       | H+3.2      | 0.5                     | 9                         | double       |
| 13  | 0.4       | H+1.2      | 0.5                     | 10                        | double       |
| 14  | 0.4       | H+2.2      | 1.0                     | 8                         | triple       |
| 15  | 0.4       | H+3.2      | 1.5                     | 9                         | single       |
| 16  | 0.5       | H+1.2      | 1.5                     | 9                         | triple       |
| 17  | 0.5       | H+2.2      | 0.5                     | 10                        | single       |
| 18  | 0.5       | H+3.2      | 1.0                     | 8                         | double       |

**Table 7.** Annual simulation results for the 18 configurations (Design Builder).

| Run       | Heating, gas (MWh) | Cooling, electricity (MWh) | Total electricity (MWh) | Total gas (MWh) | CO <sub>2</sub> reduction (kg/yr) |
|-----------|--------------------|----------------------------|-------------------------|-----------------|-----------------------------------|
| Base case | 180.24             | 26.20                      | 49.73                   | 251.58          | –                                 |
| 1         | 173.39             | 25.80                      | 49.42                   | 244.75          | 1,471                             |
| 2         | 173.11             | 25.75                      | 49.37                   | 244.47          | 1,555                             |
| 3         | 173.83             | 25.66                      | 49.27                   | 245.18          | 1,480                             |
| 4         | 174.28             | 25.63                      | 49.26                   | 245.63          | 1,404                             |
| 5         | 174.38             | 25.58                      | 49.20                   | 245.73          | 1,422                             |
| 6         | 174.16             | 25.69                      | 49.31                   | 245.52          | 1,397                             |
| 7         | 174.64             | 25.59                      | 49.21                   | 246.00          | 1,367                             |
| 8         | 174.83             | 25.55                      | 49.17                   | 246.18          | 1,354                             |
| 9         | 175.96             | 25.51                      | 49.13                   | 247.32          | 1,165                             |
| 10        | 173.10             | 25.70                      | 49.31                   | 244.46          | 1,592                             |
| 11        | 173.52             | 25.80                      | 49.41                   | 244.87          | 1,456                             |
| 12        | 173.37             | 25.78                      | 49.39                   | 244.73          | 1,495                             |
| 13        | 173.77             | 25.64                      | 49.26                   | 245.13          | 1,501                             |
| 14        | 173.96             | 25.67                      | 49.29                   | 245.31          | 1,448                             |
| 15        | 175.06             | 25.63                      | 49.25                   | 246.42          | 1,262                             |
| 16        | 175.07             | 25.53                      | 49.15                   | 246.42          | 1,320                             |
| 17        | 175.30             | 25.54                      | 49.16                   | 246.66          | 1,269                             |
| 18        | 175.20             | 25.58                      | 49.20                   | 246.55          | 1,268                             |

Every configuration reduces both heating and cooling energy and hence CO<sub>2</sub> emissions relative to the base case. The heating reduction ranges from 4.28 MWh (run 9, 2.4%) to 7.14 MWh (run 10, 4.0%). The cooling reduction ranges from 0.40 MWh (runs 1 and 11, 1.5%) to 0.69 MWh (run 9, 2.6%). The run with the largest cooling saving is thus the run with the smallest heating saving, a first indication of the conflict between the two seasons. The CO<sub>2</sub> reduction ranges from 1,165 kg (run 9) to 1,592 kg (run 10) per year; because heating is supplied by gas and dominates the energy balance, the CO<sub>2</sub> ranking follows the heating ranking closely.

In all runs, the reduction of total electricity use is 80–100 kWh smaller than the reduction of cooling electricity, i.e. some other electrical end use increases by about 90 kWh per year when the chimney is installed. A plausible cause is additional artificial lighting because the chimney modules shade part of the windows.

#### 4.4. Main effects

Table 8 and Fig. 6 show the mean response at each level of each factor, calculated from Table 7, together with the larger-the-better signal-to-noise ratios computed with Eq. (1) (in brackets).

**Table 8.** Mean response at each level (larger-the-better S/N ratio in dB in brackets), recomputed from the data of Table 7. Delta is the range of the level means; rank follows the F-ratio of Table 9.

| Objective                         | Level        | Depth            | Height           | Absorber thickness | Insulation thickness | Glazing type     |
|-----------------------------------|--------------|------------------|------------------|--------------------|----------------------|------------------|
| Heating reduction (kWh)           | 1            | 6,853<br>(76.71) | 6,198<br>(75.79) | 6,103 (75.65)      | 6,095 (75.65)        | 5,655<br>(74.93) |
|                                   | 2            | 5,972<br>(75.50) | 6,057<br>(75.58) | 5,972 (75.38)      | 5,953 (75.42)        | 6,162<br>(75.73) |
|                                   | 3            | 5,073<br>(74.07) | 5,643<br>(74.92) | 5,823 (75.26)      | 5,850 (75.22)        | 6,082<br>(75.63) |
|                                   | Delta / rank | 1,780 / 1        | 555 / 2          | 280 / 4            | 245 / 5              | 507 / 3          |
| Cooling reduction (kWh)           | 1            | 452<br>(53.04)   | 552<br>(54.72)   | 533 (54.38)        | 512 (54.05)          | 548 (54.58)      |
|                                   | 2            | 560<br>(54.95)   | 552<br>(54.68)   | 560 (54.88)        | 555 (54.76)          | 547 (54.65)      |
|                                   | 3            | 650<br>(56.25)   | 558<br>(54.83)   | 568 (54.98)        | 595 (55.43)          | 567 (55.01)      |
|                                   | Delta / rank | 198 / 1          | 7 / 5            | 35 / 3             | 83 / 2               | 20 / 4           |
| Total site-energy reduction (kWh) | 1            | 7,305<br>(77.27) | 6,750<br>(76.55) | 6,637 (76.40)      | 6,607 (76.37)        | 6,203<br>(75.77) |
|                                   | 2            | 6,532<br>(76.28) | 6,608<br>(76.36) | 6,532 (76.20)      | 6,508 (76.22)        | 6,708<br>(76.49) |
|                                   | 3            | 5,723<br>(75.13) | 6,202<br>(75.77) | 6,392 (76.08)      | 6,445 (76.09)        | 6,648<br>(76.42) |
|                                   | Delta / rank | 1,582 / 1        | 548 / 2          | 245 / 4            | 162 / 5              | 505 / 3          |
| CO <sub>2</sub> reduction (kg)    | 1            | 1,508<br>(63.56) | 1,442<br>(63.17) | 1,414 (63.00)      | 1,401 (62.92)        | 1,338<br>(62.50) |
|                                   | 2            | 1,406<br>(62.95) | 1,417<br>(63.01) | 1,405 (62.90)      | 1,398 (62.89)        | 1,435<br>(63.12) |
|                                   | 3            | 1,290<br>(62.20) | 1,344<br>(62.54) | 1,384 (62.81)      | 1,405 (62.90)        | 1,432<br>(63.10) |
|                                   | Delta / rank | 218 / 1          | 98 / 3           | 30 / 4             | 6 / 5                | 97 / 2           |

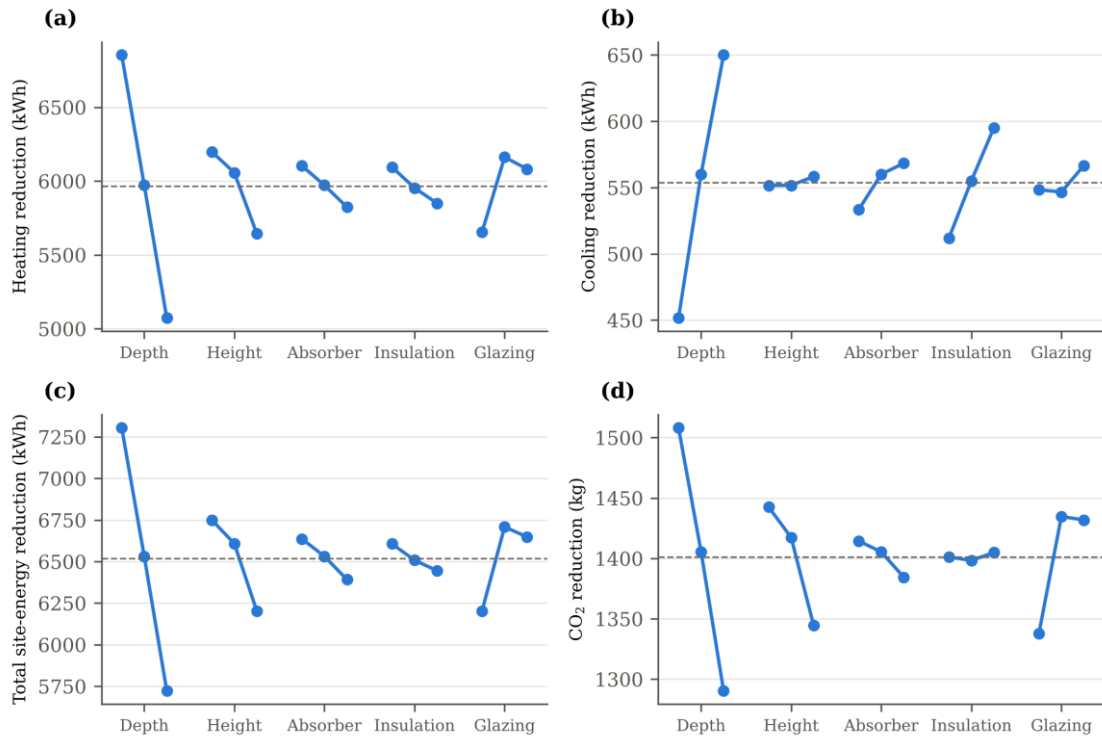


**Fig. 6.** Main effects of the five parameters on (a) heating, (b) cooling, (c) total site-energy and (d) CO<sub>2</sub> reduction. For each parameter the three points are levels 1, 2 and 3 of Table 4 from left to right; the dashed line is the grand mean.

For heating, the reduction decreases strongly with chimney depth, from 6,853 kWh at 0.3 m to 5,073 kWh at 0.5 m ( $\Delta = 1,780$  kWh). It also decreases with chimney height and with absorber and insulation thickness, and it is largest with double glazing (6,162 kWh), slightly lower with triple glazing and clearly lowest with single glazing (5,655 kWh). For cooling, the trend of depth is reversed: the reduction increases from 452 kWh at 0.3 m to 650 kWh at 0.5 m, and it also increases with insulation thickness (from 512 to 595 kWh), while height and glazing have almost no effect. The total site energy follows the heating trends because heating is about seven times larger than cooling. The CO<sub>2</sub> reduction follows heating as well, but the relative weight of glazing and height is larger, because the electricity savings, which carry a three times higher emission factor, depend more on these parameters than the gas savings do.

#### 4.5. Analysis of variance

Table 9 gives the complete ANOVA for the four objectives, and Fig. 7 compares the contributions.

**Table 9.** Analysis of variance of the L18 results (Table 7). Contribution is the pure percentage contribution,  $(SS - \text{dof} \cdot MS_e) / SST$ ; negative values are shown as 0. With deterministic simulation and no replicates, the “error” term contains interactions and higher-order effects rather than random error.

| Objective | Source               | SS         | dof | MS        | F     | p       | Contribution (%) |
|-----------|----------------------|------------|-----|-----------|-------|---------|------------------|
| Heating   | Depth                | 9,505,478  | 2   | 4,752,739 | 299.9 | < 0.001 | 79.5             |
|           | Height               | 997,878    | 2   | 498,939   | 31.5  | < 0.001 | 8.1              |
|           | Absorber thickness   | 235,478    | 2   | 117,739   | 7.4   | 0.019   | 1.7              |
|           | Insulation thickness | 181,544    | 2   | 90,772    | 5.7   | 0.034   | 1.3              |
|           | Glazing type         | 890,311    | 2   | 445,156   | 28.1  | < 0.001 | 7.2              |
|           | Error                | 110,939    | 7   | 15,848    | —     | —       | 2.3              |
|           | Total                | 11,921,628 | 17  |           |       |         | 100              |
| Cooling   | Depth                | 118,344    | 2   | 59,172    | 233.7 | < 0.001 | 80.4             |

|                   |                      |           |    |           |       |         |      |
|-------------------|----------------------|-----------|----|-----------|-------|---------|------|
|                   | Height               | 178       | 2  | 89        | 0.4   | 0.716   | 0.0  |
|                   | Absorber thickness   | 4,011     | 2  | 2,006     | 7.9   | 0.016   | 2.4  |
|                   | Insulation thickness | 20,844    | 2  | 10,422    | 41.2  | < 0.001 | 13.9 |
|                   | Glazing type         | 1,478     | 2  | 739       | 2.9   | 0.120   | 0.7  |
|                   | Error                | 1,772     | 7  | 253       | –     | –       | 2.9  |
|                   | Total                | 146,628   | 17 |           |       |         | 100  |
| Total site energy | Depth                | 7,506,233 | 2  | 3,753,117 | 267.3 | < 0.001 | 76.7 |
|                   | Height               | 972,233   | 2  | 486,117   | 34.6  | < 0.001 | 9.7  |
|                   | Absorber thickness   | 181,300   | 2  | 90,650    | 6.5   | 0.026   | 1.6  |
|                   | Insulation thickness | 79,633    | 2  | 39,817    | 2.8   | 0.125   | 0.5  |
|                   | Glazing type         | 913,300   | 2  | 456,650   | 32.5  | < 0.001 | 9.1  |
|                   | Error                | 98,300    | 7  | 14,043    | –     | –       | 2.4  |
|                   | Total                | 9,751,000 | 17 |           |       |         | 100  |
| CO <sub>2</sub>   | Depth                | 142,297   | 2  | 71,148    | 158.6 | < 0.001 | 65.5 |
|                   | Height               | 31,084    | 2  | 15,542    | 34.6  | < 0.001 | 14.0 |
|                   | Absorber thickness   | 2,836     | 2  | 1,418     | 3.2   | 0.105   | 0.9  |
|                   | Insulation thickness | 127       | 2  | 64        | 0.1   | 0.870   | 0.0  |
|                   | Glazing type         | 36,441    | 2  | 18,221    | 40.6  | < 0.001 | 16.5 |
|                   | Error                | 3,141     | 7  | 449       | –     | –       | 3.5  |
|                   | Total                | 215,926   | 17 |           |       |         | 100  |

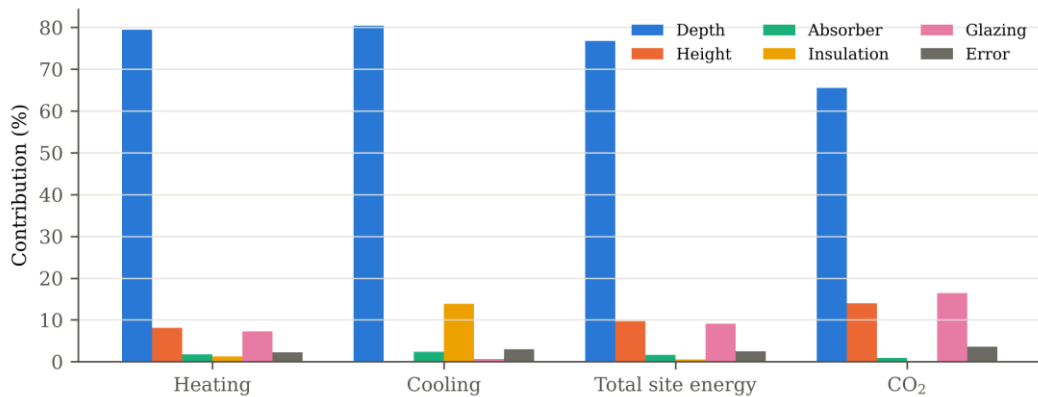


Fig. 7. Pure percentage contribution of each parameter and of the error term to the four objectives.

Chimney depth is the dominant parameter for every objective, with a pure contribution of 79.5% for heating, 80.4% for cooling, 76.7% for total site energy and 65.5% for CO<sub>2</sub> (all  $p < 0.001$ ). For heating, the second-order parameters are height (8.1%) and glazing (7.2%), both with  $p < 0.001$ ; absorber thickness (1.7%,  $p = 0.019$ ) and insulation thickness (1.3%,  $p = 0.034$ ) have small but detectable effects. For cooling, insulation thickness is the second parameter (13.9%,  $p < 0.001$ ), followed by absorber thickness (2.4%,  $p = 0.016$ ); height ( $p = 0.72$ ) and glazing ( $p = 0.12$ ) have no detectable effect. For CO<sub>2</sub>, glazing (16.5%) and height (14.0%) are more important than for heating, whereas absorber ( $p = 0.11$ ) and insulation ( $p = 0.87$ ) have no detectable effect. The error term, which contains the interactions neglected by the main-effects model, accounts for only 2.3–3.5% of the variation; in the space of the 18 runs, the main-effects model therefore describes the responses well.

#### 4.6. Optimal levels and predicted performance

Table 10 gives the optimal level of each parameter for each objective, i.e. the level with the largest mean response, and the performance predicted by the additive model (Eq. 3).

**Table 10.** Optimal levels for each objective and performance predicted by the additive Taguchi model.

| Objective         | Depth (m) | Height (m) | Glazing | Insulation (cm) | Absorber (cm) | Predicted reduction (95% CI) |
|-------------------|-----------|------------|---------|-----------------|---------------|------------------------------|
| Heating           | 0.3       | H+1.2      | double  | 8               | 0.5           | 7,547 ± 233 kWh              |
| Cooling           | 0.5       | H+3.2      | triple  | 10              | 1.5           | 723 ± 29 kWh                 |
| Total site energy | 0.3       | H+1.2      | double  | 8               | 0.5           | 7,927 ± 219 kWh              |
| CO <sub>2</sub>   | 0.3       | H+1.2      | double  | 10              | 0.5           | 1,599 ± 39 kg/yr             |

The optimal settings for heating and cooling are opposite for four of the five parameters. Heating benefits from a shallow, short chimney with a thin absorber: a narrow channel heats the supply air to a higher temperature, and a thin absorber of low thermal mass delivers the collected heat quickly during the short winter day. Cooling benefits from a deep, tall chimney, which increases the buoyancy-driven exhaust flow, and from thicker insulation and a heavier absorber, which limit heat transfer from the hot channel to the rooms. The CO<sub>2</sub> optimum combines the heating optimum with the thickest insulation, but the effect of insulation on CO<sub>2</sub> is not significant ( $p = 0.87$ ), so 8 and 10 cm are practically equivalent for this objective.

Because heating dominates the annual balance, the heating optimum is also the optimum for total site energy and almost the optimum for CO<sub>2</sub>, and it requires the least material (single-storey height, 8 cm insulation, double rather than triple glazing). This combination was therefore selected as the final design: depth 0.3 m, height H+1.2, absorber 0.5 cm, insulation 8 cm, double glazing. For this design the additive model predicts a heating reduction of  $7,547 \pm 233$  kWh (4.2%), a cooling reduction of  $379 \pm 29$  kWh (1.4%), a total site-energy reduction of  $7,927 \pm 219$  kWh and a CO<sub>2</sub> reduction of  $1,595 \pm 39$  kg per year. The selected combination is not one of the 18 runs of the array (the closest run, run 1, differs only in having single glazing), so a confirmation simulation is required.

#### 4.7. Confirmation and comparison with the base building

Table 11 compares the base building with the predicted performance of the selected design, with the best configuration actually simulated (run 10) and with the confirmation run.

**Table 11.** Annual energy use and CO<sub>2</sub> emissions of the base building and of the solar-chimney designs.

| Case                                     | Heating (kWh/yr)                    | Cooling (kWh/yr)                | CO <sub>2</sub> (kg/yr)           |
|------------------------------------------|-------------------------------------|---------------------------------|-----------------------------------|
| Base building                            | 180,240                             | 26,200                          | 77,328                            |
| Selected design, Taguchi prediction      | 172,693 ( $-7,547 \pm 233$ ; -4.2%) | 25,821 ( $-379 \pm 29$ ; -1.4%) | 75,733 ( $-1,595 \pm 39$ ; -2.1%) |
| Selected design, confirmation run        | 172,820 ( $-7,420$ ; -4.1%)         | 25,810 ( $-390$ ; -1.5%)        | 75,751 ( $-1,577$ ; -2.0%)        |
| Best simulated run of the array (run 10) | 173,100 ( $-7,140$ ; -4.0%)         | 25,700 ( $-500$ ; -1.9%)        | 75,736 ( $-1,592$ ; -2.1%)        |

The confirmation run of the selected design reduced heating energy by 7,420 kWh (4.1%), cooling energy by 390 kWh (1.5%) and CO<sub>2</sub> emissions by 1,577 kg per year. All three values lie within the 95% confidence intervals of the additive-model predictions ( $7,547 \pm 233$  kWh,  $379 \pm 29$  kWh and  $1,595 \pm 39$  kg), which indicates that interactions between the factors are small and that the additive model is adequate. The selected design saves about 0.3 MWh more heating energy than the best run of the array (run 10), whereas run 10 saves more cooling energy (500 kWh) because it uses 10 cm of insulation and triple glazing; the CO<sub>2</sub> reductions of the two designs are practically equal. Both designs reduce heating energy by about 4%, cooling energy by 1.5–1.9% and CO<sub>2</sub> emissions by about 1.6 t per year.

#### 4.8. Airflow and channel temperatures

Table 12 reports the airflow and channel air temperatures of one chimney module for a clear winter day (21 January) and a clear summer day (21 July), for the selected design and for the deepest channel. In winter the shallow

channel delivers less air (105 versus 152 m<sup>3</sup>/h at the peak) but at a much higher temperature (31.5 versus 23.4 °C), so it supplies more useful heat to the room (6.1 versus 5.0 kWh per day). In summer the deep channel exhausts about 45% more air for a similar buoyancy pressure. These values confirm that the openings carried airflow in both modes and support the physical interpretation given in Section 5.1; they are also of the same order as the flows predicted by the steady-state model of Ong [9] for comparable gap widths and heights.

**Table 12.** Airflow and channel air temperature of one chimney module (selected height, glazing, insulation and absorber) on representative clear days.

| Quantity                                     | Winter day, D = 0.3 m | Winter day, D = 0.5 m | Summer day, D = 0.3 m | Summer day, D = 0.5 m |
|----------------------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Outdoor air temperature at 13:00 (°C)        | 7.0                   | 7.0                   | 36.4                  | 36.4                  |
| Peak airflow per module (m <sup>3</sup> /h)  | 105 (supply)          | 152 (supply)          | 128 (exhaust)         | 186 (exhaust)         |
| Peak channel-outlet air temperature (°C)     | 31.5                  | 23.4                  | 46.8                  | 42.2                  |
| Daily useful heat delivered per module (kWh) | 6.1                   | 5.0                   | –                     | –                     |
| Hours with chimney airflow                   | 7.5                   | 7.5                   | 11.0                  | 11.0                  |

## 5. DISCUSSION

### 5.1. Physical interpretation

The results show that a single geometric parameter, the depth of the air channel, governs the performance of the chimney in both seasons, but in opposite directions. In winter the chimney acts as a solar air heater: for a given absorbed solar flux, a narrow channel carries less air at a higher temperature, so the preheated air delivered to the rooms is warmer and a larger fraction of the collected energy offsets the heating load rather than being lost through the glazing. In summer the chimney acts as an exhaust stack: a deeper channel has a lower flow resistance and carries a larger exhaust flow for the same buoyancy pressure, which enhances the ventilation of the dwellings. The literature value of 0.2–0.3 m for the optimal gap [2, 11] refers mainly to ventilation performance; the present results suggest that, in heating mode, the optimum lies at or below the lower end of the investigated range.

Height acts in a similar but weaker way: a taller chimney increases the glazed area and the heat losses in winter more than it increases the useful heat, whereas its benefit for the summer stack effect is hardly visible ( $p = 0.72$  for cooling). Glazing matters for heating and CO<sub>2</sub> because single glazing loses too much heat from the warm channel, while the additional resistance of triple glazing does not compensate for its lower solar transmittance. Insulation thickness matters for cooling, where it limits the heat flow from the hot channel to the rooms, but hardly for heating, where the useful heat is delivered by the supply air rather than through the wall. The thin absorber is preferred in winter because its low thermal mass responds quickly to the available solar radiation.

### 5.2. Magnitude of the savings and model uncertainty

The best configurations reduce heating energy by about 4%, cooling energy by 1.5–2.6% and CO<sub>2</sub> emissions by about 2% of the building total. These savings are real but modest, and they should be interpreted together with the uncertainty of the building model. The monthly calibration errors (NMBE of 3.6% for gas and -3.4% for electricity) are of the same order as the heating saving itself, and the differences between the 18 configurations (about 3 MWh, or 1.6% of the heating demand, between the best and the worst run) are smaller still. Because all configurations are simulated with the same model, systematic errors largely cancel in the comparison between configurations, so the ranking of the parameters is more reliable than the absolute savings. The absolute values should be regarded as estimates with an uncertainty of the same order as the savings, and a monitored prototype would be needed to confirm them.

The savings should also be put in relation to the scale of the intervention. The twelve chimney modules (two per residential floor) have a total glazed collector area of 25.8 m<sup>2</sup>. The heating saving of the selected design, 7,420 kWh per year, therefore corresponds to about 290 kWh per m<sup>2</sup> of collector per year, which is within the range reported for unglazed and glazed solar air heaters in sunny climates, but only 3.4 kWh per m<sup>2</sup> of floor area of the building.

### 5.3. Environmental and economic balance

The CO<sub>2</sub> objective in the optimisation accounts only for operational emissions, but the chimney itself carries embodied emissions. Using the material quantities of the selected design and the coefficients of the Inventory of Carbon and Energy [20], the embodied carbon per m<sup>2</sup> of collector is approximately 17 kg CO<sub>2</sub> for the double glazing (20 kg of glass at 0.85 kg CO<sub>2</sub>/kg), 37 kg for the aluminium frame (4 kg at 9.16 kg CO<sub>2</sub>/kg), 57 kg for the 0.5 cm steel absorber (39 kg at 1.46 kg CO<sub>2</sub>/kg), 35 kg for the 2 cm PCM layer (17.6 kg at an assumed 2.0 kg CO<sub>2</sub>/kg, for which ICE gives no value) and 8 kg for the 8 cm polyurethane insulation (2.4 kg at 3.48 kg CO<sub>2</sub>/kg), i.e. about 155 kg CO<sub>2</sub> per m<sup>2</sup>. For 25.8 m<sup>2</sup>, and with a 20% allowance for fixings, sealants and transport, the embodied carbon is about 4.8 t CO<sub>2</sub>. With an operational saving of 1.58 t CO<sub>2</sub> per year, the carbon payback time is therefore about 3 years, well below the expected service life of the components. The economic payback is much less favourable: at the heavily subsidised domestic gas and electricity prices in Iran, the annual monetary saving is small, so the economic case depends on energy-price reform or on valuing the avoided emissions. The selected design is also the least material-intensive of the alternatives, because it uses the shortest chimney, the thinnest absorber, the thinnest insulation and double rather than triple glazing.

### 5.4. Limitations

**Experimental validation.** The simulation approach was verified against a published simulation case, not against measurements of a solar chimney. An experimental validation, ideally with measured channel temperatures and airflow rates, would considerably strengthen the conclusions.

**Representation of airflow.** Whole-building energy models represent the airflow in a solar chimney in a simplified way. In the screening stage, some vent arrangements gave identical annual results, which suggests that their additional openings carried little or no airflow; for the selected arrangement, however, the airflow rates of Table 12 confirm that the chimney operates in both modes. Comparison with CFD for representative days would further strengthen confidence in the airflow model.

**Parameter ranges.** The optimal levels of depth, height and insulation for heating lie at the boundary of the investigated range. The true optimum is therefore probably outside the range, and a follow-up study with shallower and shorter chimneys, or a response-surface design around the optimum, is recommended.

**Main-effects model.** The L18 array estimates main effects only. The error term is small within the array (2.3–3.5%), and the confirmation run of the selected design, which lies outside the array, fell within the prediction intervals for all three objectives (Section 4.7).

**Single building and climate.** The results apply to one building, one orientation and one climate. The relative importance of the parameters may differ for other orientations, building types and climates.

**Thermal comfort.** The analysis is based on annual energy use. The effect of the chimney on indoor air temperature, on the risk of overheating in the shoulder seasons and on indoor air quality was not assessed.

## 6. CONCLUSIONS

A segmented dual-season solar chimney integrated into an eight-storey residential building in Tehran was designed, modelled in Design Builder and optimised with a Taguchi L18 design and analysis of variance. The main conclusions are:

1. **The geometry decides whether the chimney saves heating energy.** A continuous chimney over the façade height and a two-storey chimney per floor increased the heating demand, whereas two single-storey modules per floor reduced it. The vent arrangement had a much smaller influence.
2. **Among the 18 configurations of the L18 array,** the chimney reduced heating energy by 2.4–4.0%, cooling energy by 1.5–2.6% and CO<sub>2</sub> emissions by 1.17–1.59 t per year.
3. **Chimney depth is the dominant design parameter** for heating, cooling, total site energy and CO<sub>2</sub> (pure contribution 65–80%,  $p < 0.001$ ), followed by height and glazing for heating and CO<sub>2</sub> and by insulation thickness for cooling.
4. **Heating and cooling favour opposite designs:** a shallow, short chimney with a thin absorber for heating, and a deep, tall, well-insulated chimney for cooling. Because heating dominates the annual energy balance of the building, the heating optimum (0.3 m depth, H+1.2 m height, 0.5 cm absorber, 8 cm insulation, double glazing) also minimises total site energy and practically minimises CO<sub>2</sub>.
5. For this design the additive model predicts a heating reduction of  $7.55 \pm 0.23$  MWh (4.2%), a cooling reduction of  $0.38 \pm 0.03$  MWh (1.4%) and a CO<sub>2</sub> reduction of  $1.60 \pm 0.04$  t per year; the confirmation run gave 7.42 MWh, 0.39 MWh and 1.58 t, all within the prediction intervals.
6. The savings are modest compared with the uncertainty of the building model, but the carbon payback time of the chimney is only about 3 years; the economic payback depends strongly on energy prices.

Future work should validate the model experimentally with measured channel temperatures and airflow rates, extend the parameter ranges towards shallower and shorter chimneys, assess thermal comfort and indoor air quality, and evaluate the economic balance of the system under different energy-price scenarios.

### **Data Availability**

The simulation results used in the statistical analysis are reported in Table 7, and the analyses can be reproduced with these data and the equations in Section 3.5. In this teaching version, the Design Builder model files and the Python script are available from the course instructor.

### **Declaration of Competing Interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### **Ethics Statement**

This study was based on building energy simulations and did not involve human participants or the collection of personal data.

### **Declaration of Generative AI Use**

During the preparation of this manuscript, the authors used generative AI tools to improve the language and readability of the text. The authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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