

The Z free home from conceptual design to simulation results

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Abstract

The need for affordable housing requires more compact living. With the increasing frequency and impact of climate change incidents, a new way of thinking is needed to live in a more resilient and climate responsive way. The idea of a Z free home began by considering these two needs. As a tiny mobile house equipped with passive and eco-cycle systems, it achieves 9 zero targets. This paper evaluates the design concept, building modelling, and building simulation for the Z free home design. The project is ongoing and aims to model a full physical prototype as a proof of concept for the 9 zero targets in an urban living lab context in Lund Sweden.

Introduction

Study background

Limited global resources and the mounting climate crisis are among the greatest challenges faced by humankind today. There is a growing recognition that there is no planet B and that addressing climate change, biodiversity loss, mass extinction, environmental damage and pollution may be the principal challenges of our time (Hes & Du Plessis, 2015). Building and construction account for more than 36% of global energy use and 39% of energy-related carbon dioxide (CO₂) emissions (IEA, 2019). Moreover, over four million deaths each year are attributable to illness from household air pollution (IPCC, 2018). In recent years, the building sector has moved towards more energy and resource efficient materials and construction methods, yet as the world's population continues to grow and urbanize, energy demands from the construction industry outpace progress towards the green transition. Over the next 40 years, it is expected that 230 billion square metres in new construction will be built worldwide, the equivalent of adding a city the size of Paris to the planet every single week (REN21, 2018).

In conventional mass building, using industrial materials is the quickest and easiest solution. Environmental impact is not considered a high priority. Fortunately, many

opportunities exist to deploy energy-efficient and low-carbon, passive and eco-cycle solutions for buildings and construction (Dabaieh, 2016; Dabaieh & Serageldin, 2020; Lucas, 2021). While such ideas are not yet mainstream in the building market, especially within the residential sector, the Sustainable Development Goals are giving new purpose to businesses, their buildings, and how they are designed, constructed and used (French & Kotzé, 2018). Ambitious action is needed without delay to avoid locking in long-lived, inefficient buildings for decades to come.

The Z free home concept

The Z free home is a high risk, high gain, eco-cycle tiny home representing a return to natural design solutions inspired from vernacular architecture's passive and low impact strategies. The tiny 20 m² house is designed to be built using bio-based fibres that are sometimes considered agriculture waste. The building's design is based on natural zero energy solutions that function year-round and produce more energy than the building consumes. The house's performance offsets all carbon emissions produced throughout its lifetime and aims to reach a negative carbon footprint. When it is time to demolish the building, all main building components can be re-used as building materials, animal feed, or biofuel. If not, they can decompose as compost and return to nature.

Three passive design systems are used for passive heating and cooling. These include the Trombe wall, green wall, and Earth Air Heat Exchanger (EAHE). The idea is to maximise the use natural resources – sun, wind, and geothermal – to reduce carbon-intensive heating and cooling demands. The house is equipped with photovoltaic panels for energy production and a solar water heater. All organic waste and wastewater will be recycled and reused again leaving zero waste behind. This house is a unique challenge as it aims to achieve zero energy, zero cooling, zero heating, zero waste, zero carbon, zero labour costs (if you build it yourself), zero materials costs, zero impact on the environment (when the building is demolished) and zero maintenance required (for the first 20 years of the first cycle of the house).

The methodological approach followed in this project is participatory and relies on transdisciplinary research. The design was conceptualised through participatory workshops with a number of potential tenants. They were asked what they required for living in the house. Then, they were consulted for their acceptance and/or interest in using eco-cycle and passive heating, cooling, and ventilation systems. As passive and eco-cycle systems need direct inputs from occupants in order to function optimally, it was important to involve potential tenants in the design stage. Several experts and practitioners, such as engineers, craftsmen and technicians were also consulted on technical issues related to the design. The plan is to build the house prototype in collaboration with volunteers to test the feasibility of the ‘do it yourself’ construction process. This paper will focus on the detailed building simulation as part of the methodological steps that serves as the design decision making support for all different passive and low impact eco-cycle systems. The house design is shown in Fig. 1, 2 and 3.

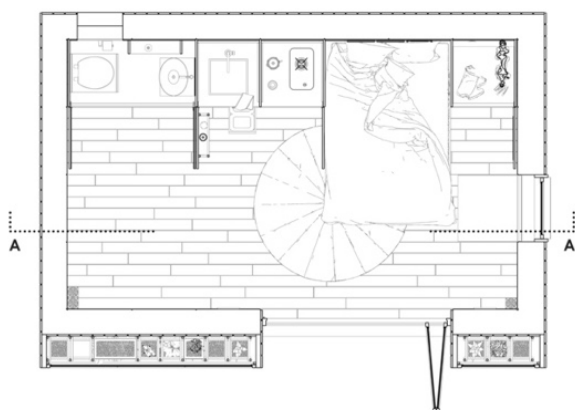


Figure (1) A plan of the Z Free Home, showing interior amenities for eco-cycle compact living.



Figure (2) Section AA shows the detailed design for all eco-cycle details in the bathroom and kitchen integrated with furniture.

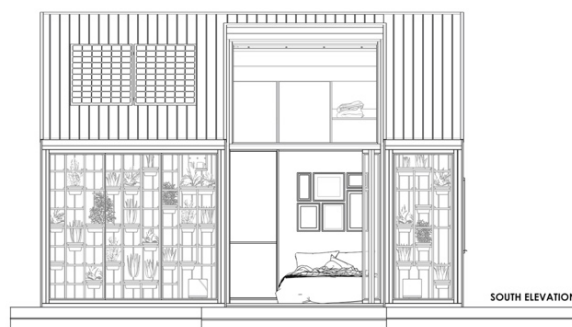


Figure (3) The house's southern façade showing the integrated design of the hybrid Trombe wall and the green wall as passive systems.

This paper will explain the simulation process and discuss the outcomes of the building's energy performance, thermal performance, and the expected efficiency of the passive systems used for heating, cooling, natural ventilation, and daylight. Results from testing a simulation of the proposed low impact building envelope using natural materials and passive eco-cycle systems will also be provided. This experimental project will be built in Lund, Sweden as a proof of concept to be monitored for its efficiency for one year onsite. This paper will only focus on the simulation stage as part of the project's methodological steps.

Methods

This paper focuses on the moisture, energy and thermal comfort, daylight, and production of electricity in relation to the Z free home. Different simulation tools and diagrams are used to model the building's energy requirements. In the below sections the methods are explained in detail.

Moisture safety simulations

For the moisture safety analysis, the simulation software WUFI was used. WUFI is a license-based software that allows for the calculation of non-stationary heat and moisture transfer in walls and other parts of a building's envelope. The climate data used for the simulations were taken from the WUFI database for the city of Lund, Sweden. Simulations were conducted for a period of 10 years to accommodate for future changes in the earth's climate.

To assess the WUFI simulation results, a license-based programming platform, called MATLAB, was used. The script used with MATLAB is based on the Viitanen model for wood – spruce original kiln-dried (Hukka & Viitanen, 1999). The orientation of the wall was set to north in the WUFI simulation, as this orientation receives very little solar radiation. The indoor climate condition was set to humidity class 2 according to the standard EN13788. Construction specifications for the building envelope are

provided in Table 1. Window types are provided in Table 2.

Table 1: Material composition of the exterior constructions (from the inside to the outside)

Material	Thickness [m]	Thermal Conductivity [W/mK]	Water Vapour Diffusion Resistance Factor [-]
Claytec			
Blähtonleichtlehm	0.15	0.21	7
Thermo Jute 100 Naturbo	0.26	0.039	1.2
Innendämmplatte Lehmputz Naturbo	0.01	0.76	7
Innendämmplatte Holzweichfaser	0.06	0.042	7
Weather resistive barrier (sd = 0.1 m)	0.001	2.3	100
Larch wood	0.02	0.13	108
U-value: 0.11 W/(m²K)			

Thermal bridges were calculated using HEAT2 software. All parts of the building envelope were reproduced in HEAT2 according to the description in Table 1. Steady-state calculations were conducted. The indoor temperature was set to 21 °C, the outdoor temperature was set to -12.90°C for wall and roof calculations, and 1.22 °C for ground slab calculations. Thermal bridges for the corners of the walls, a junction between the roof and the wall, and a junction between the ground slab and the wall were also calculated. The lowest temperatures for the outdoor climate were used to assess the worst conditions for the building. First, the ideal wall, roof, and ground slab conditions were simulated to produce ideal heat flows, and then a simulation of thermal bridges was conducted. Calculations for psi-values were done according to equation 1:

$$\Psi = \frac{q_3 \cdot L_1 + q_4 \cdot L_2 - (q_1 \cdot L_1 + q_2 \cdot L_2)}{\Delta T} \quad (1)$$

q_1 – heat flow through the first ideal construction, W/m².
 q_2 – heat flow through the second ideal construction, W/m².

q_3 – heat flow through the first construction with thermal bridge, W/m².

q_4 – heat flow through the second construction with thermal bridge, W/m².

L_1 – length of the wall, m.

L_2 – length of the ground slab, m.

ΔT – temperature difference between indoor air and outdoor air, K.

Ψ – psi-value - measure of heat loss through thermal bridge, W/mK.

After the simulations of the thermal bridges, the psi-value was used to calculate a new U-value for the walls according to equation 2:

$$U_{added} = \frac{\sum \Psi_{thermal\ bridge} \cdot L_{thermal\ bridge}}{(A_{facade} - A_{windows})} \quad (2)$$

U_{added} – U-value, added to the U-value of the walls to include thermal bridges, W/m²K.

$\Psi_{thermal\ bridge}$ – psi-value of different thermal bridges, W/mK.

$L_{thermal\ bridge}$ – length of different thermal bridges, m.

A – area of the parts of the building's envelope, m².

The resulting values were incorporated into Climate Studio, a plug-in for Grasshopper, which is a computer-based simulation tool.

The different types of windows simulated using WUFI are provided in Table 2.

Table 2: Window types

Type of window	U-value [W/m²K]	g-value	Visual transmittance
Hammerglass Insulate triple glazing for the skylight (HmG06-16-FE4)	0.66	0.48	0.66
Hammerglass Insulate double glazing for windows and doors (SFE4-14-HmG06-16-SFE4)	1.53	0.70	0.74

Assessment of energy use and thermal comfort

The existing model was created in Rhinoceros 7 3D software. Energy and daylight simulations were performed in the computer-based simulation tool Climate Studio. The climate data used for the energy use and daylight simulations is stored in an .epw file, taken from the Climate One Building database (One Building, 2022). It was used to represent a typical meteorological year in Malmö, Sweden, with data from 2004 to 2018, since there is no verified file for Lund. The distance between Malmö and Lund is 16 KM.

According to the Swedish National Board of Housing, Building and Planning's constitutional requirements (BFS) 2017:6 BEN 2 (Boverkets författningssamling, 2017) for apartment buildings, 21 °C was used for the heating setpoint and 26°C was used for the cooling setpoint. The ventilation rate was set to 0.35 l/s/m², according to the BBR: BFS 2020:4 (Boverkets byggregler, 2020, p. 95) requirement. The floor area of the planned building is equal to 20 m². The heat recovery efficiency of the AHU in the planned building is 85 %.

According to BEN 2 (Boverkets författningssamling, 2017) and the Swedish environmental building standard 'Miljöbyggnad' (SGBC, 2021a), together with passive housing standards, the EUI for a passive house should be lower than 75 kWh/m² annually, with heating demand slower than 15 kWh/m² annually, or peak heating and cooling energy demands lower than 10 W/m² (Passivhaus, 2021). The energy consumption analysis was mainly focused on heating and cooling equipment, and domestic hot water.

Infiltration was calculated to measure the level of airtightness of the construction, based on the equation 3. In this calculation, an infiltration rate @50Pa was set to 0.3 l/s/m² in accordance with FEBY (Feby 18, 2019) building requirements.

$$\text{ACH(at 4Pa)} = \frac{\text{Volume of air leakage per hour}}{\text{volume of the building} * 0.204} = \frac{\left(\frac{\text{infiltration rate@50Pa}}{1000}\right) * \text{Envelope area} * 3600}{\text{Volume of the building} * 0.204} \quad (3)$$

The internal load is a sum of the weight of people occupying the building, 'people load', and the internal load of the building itself, 'equipment load'. The internal load was calculated based on equation 4 for 'people load' and on equation 5 for 'equipment load', according to BEN 2 (Boverkets författningssamling, 2017),

$$\text{People load [W/m}^2\text{]} = \frac{p * L}{A}, \quad (4)$$

A[m²] – floor area,

L – heat load per person[80 W],

p = 1.42 (1 room)

$$\text{Equipment load [W/m}^2\text{]} = f * \frac{E * 1000}{8760}, \quad (5)$$

E – household equipment energy [30 kWh/m²a],

f = usable heat fraction [70%]

The results of this calculation gave 5.39 W/m² for 'people load', and 2.68 W/m² for 'equipment load', equalling a total of 8.07 W/m² in internal gains for the building.

In this case, the equipment load includes electric lighting, fans and pumps, and domestic appliances.

Due to the setup of Climate Studio, the default EUI value extracted from the simulation is not accurate. In Climate Studio, the heat generated from the building's occupants is included in 'equipment'. However, with this set-up, the program considers people as equipment, which means a part of EUI is falsely included to supply the heat of people. Moreover, a ground-air heat exchanger is used for heating and cooling the space, which decreases the energy consumption from Climate Studio simulations. Therefore, a separate calculation for the actual EUI was required and

the equation below was employed in accordance with BEN 2 (Boverkets författningssamling, 2017).

$$EUI = E_{\text{equipment}} + E_{\text{domestic hot water}} + E_{\text{heating}} \quad (4)$$

Thermal comfort is measured through the overheating hours ratio in summer. According to FEBY18 (Feby18, 2021), overheating is defined as the temperature of a specific zone above 26°C, and its occurrence should not exceed 10% of the period from April to September. Zone operative temperature data was extracted from Climate Studio.

The EAHE is simulated separately in the PHLuft (Institut, 2022) software from the Passive House Institute, and its results were implemented manually in the Climate Studio simulation.

To mitigate the risk of overheating, a wide spectrum of approaches was employed to reduce heat gain in summer, without increasing the heating demand in winter. These include applying internal shading to the windows, using blinds during night-time hours to avoid night cooling and during the summer to avoid overheating. Natural ventilation for the period between April and September, with a temperature setpoint for outdoor air equal to 18°C and an upper limit of outdoor air temperature equal to 30°C, was also implemented in this project as an additional measure to reduce overheating.

Daylight simulations

Material reflective properties and glazing properties were assigned in Climate Studio after the 3D modelling. The sensor grid was set to 0.5x0.5 m for each point, to generate precise data. The building was analysed for spatial daylight autonomy (sDA), daylight factor (DA) and daylight glare probability (DGP). The simulation was run with a ground reflectance set to 0.1. The building was assumed to be used the whole day. The evaluation was conducted at 0.85 m above the surface of the floor. The interior material was considered to have a reflectance rate of 20.58% and RGB colour codes 222, 191, 130. Daylight autonomy was considered achieved when a point received an illuminance score of at least 300 lux. The calculations were compared with the Swedish environmental building standard 'Miljöbyggnad', (SGBC, 2021a), LEED standard 4.1 (Council, 2019), and according to the European Union requirement EN 17037 (European Union, 2022).

Venetian blinds were added and simulated to avoid potential issues related to glare. It was noted that the position of the venetian blinds should be manually readjusted at different times of day when an intolerable glare is observed.

Electricity production simulations

Energy production by photovoltaic installation (PV) was calculated in the System Advisor Model. Reference conditions for the PV installation include 1000 W/m^2 for total irradiance and 25°C for cell temperature. PV installation was simulated for the city of Malmö. Photovoltaic modules in the simulation are Canadian Solar CS3K-300MS modules ($1633 \times 992 \times 35 \text{ mm}$), with 20.64 % nominal efficiency. The Solar Power YS YS-3000TL inverter was used at 240 V to connect directly into the house's grid. The solar installation consisted of 5 modules per string in 2 parallel strings. Simulation included losses, to compensate for the module mismatch (2%), diodes and connections (0.5 %), wiring (2 %), as well as soiling (5 % annually). The system covers, in total, 16 m^2 of the roof's surface, reserving space to conduct maintenance. After conducting the simulations, it was noted that roof space should also be reserved for batteries, so that the overproduction of energy in mornings and afternoons as well as over summer can be stored and compensate for the lack of electricity produced at night and over winter.

Results

Moisture safety assessment

First, of all components of the building's envelope were simulated to assess the moisture safety. Results of the moisture safety assessment for the most important layers of the building's envelope are provided below. Results of the mould index analysis of the interior side of the larch layer are provided in Fig. 4. The mould index in the larch layer peaks within the first two years, but gradually decreases in the following years, meaning that there is no danger of mould growth in that layer.

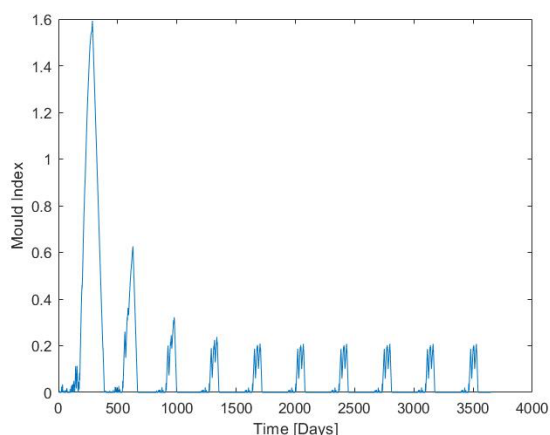


Figure 4: Results of the mould index analysis of the interior side of the larch layer.

Results of the mould index analysis of the holzweichfaser layer are provided in Fig. 5 and similarly shows that mould growth is significant within the first few years but drops to 0 after that.

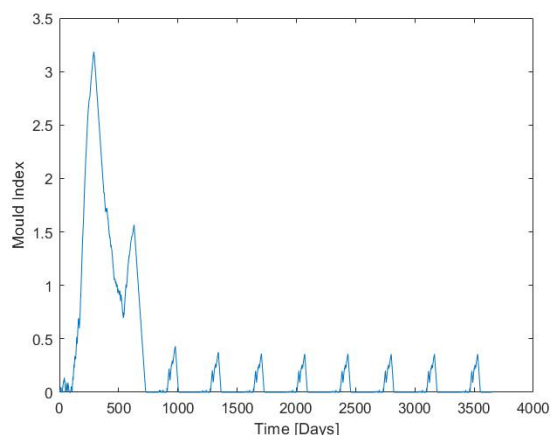


Figure 5: Results of the mould index analysis of the holzweichfaser layer.

Results of the mould index analysis of the lehmputz layer are provided in Fig. 6. Mould growth appears during the first few years and disappears after that.

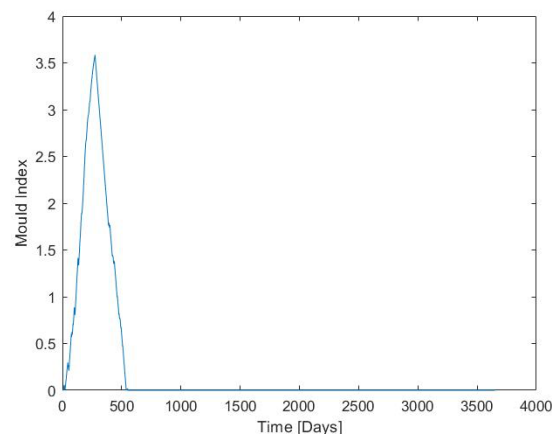


Figure 6: Results of the mould index analysis of the lehmputz layer.

Results of the mould index analysis of the thermo jute layer are provided in Fig. 7. Results from the simulation indicate very significant mould growth in the first 2 years, followed by a drop to zero.

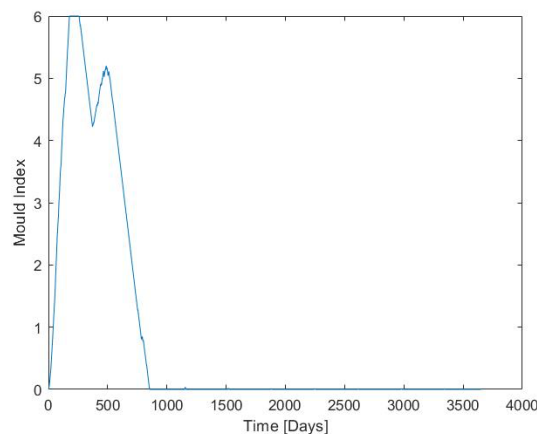


Figure 7: Results of the mould index analysis of the thermo jute layer.

The outcome of the moisture simulation proves that the building envelope using the suggested layers of breathable natural building materials is moisture safe.

Energy use and thermal comfort assessment

Results from the energy and thermal comfort simulations are shown in Table 3 and demonstrate that the Z free home fits within accepted Swedish and international standards of a passive house.

Table 3: Energy and thermal comfort simulation results

Parameter	Value
EUI, kWh/m ² y	73.28
Overheating ratio over summer, %	0.31%
Heating load after the ground heat exchanger, kWh/m ² y	10.25
Cooling load after the ground heat exchanger, kWh/m ² y	13.03
Equipment load, kWh/m ² y	30.00
Hot water load, kWh/m ² y	20.00
Total electricity consumption, kWh/y	1465.67

Results of simulations for the total electricity consumed include heating load, cooling load, domestic appliances, electric lighting and fans and pumps. The operative temperature, provided in fig. 8, shows that the building has a very low percentage of time where occupants would experience thermal discomfort. Most hours of the day, and year, are in a temperature range between 21°C and 26°C. This means that the building fits into the Swedish National Board of Housing, Building and Planning's regulations (BEN2) requirement for thermal comfort for residential buildings.

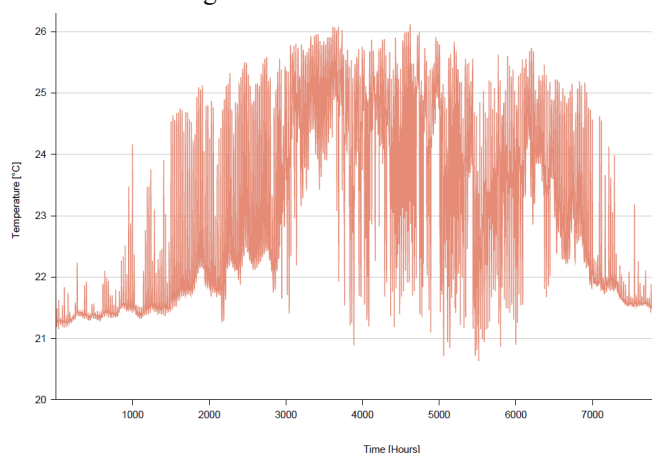


Figure 8: Indoor temperature on the hourly scale for the whole year.

Daylight simulations

For the daylight simulations, analyses for three values were assessed – DF, sDA and DGP. The results of the DF analysis are shown in Fig. 9. The uniformity of daylight access is low; however, for the main workspace positions, the daylight factor is high enough.

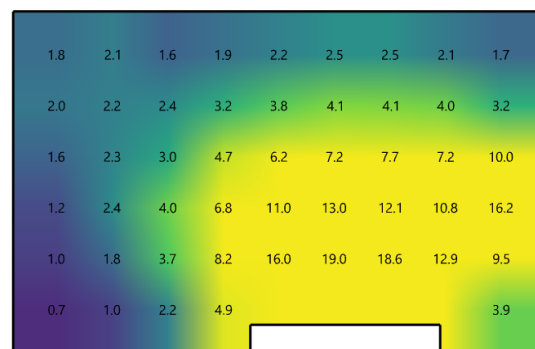


Figure 9: Results of the daylight factor analysis

The results of the sDA analysis are shown in Fig. 10. These results demonstrate that most of the room has enough daylight access to circumvent the use of electric lighting during daylight hours. The green areas of Fig. 10 depict areas of the Z free home compliant with LEED 4.1.

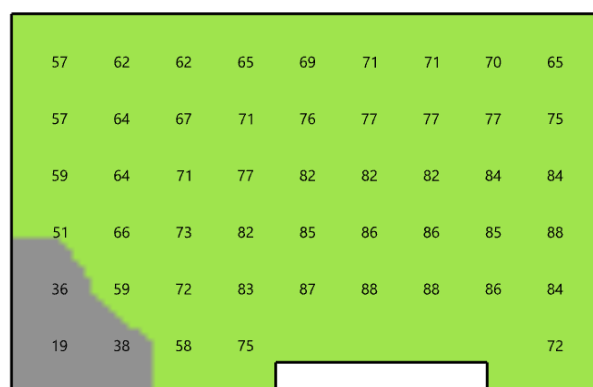


Figure 10: Results of sDA analysis

The results of the annual DGP analysis are shown in Fig. 11. These results illustrate that a high percentage of views have an intolerable glare, but the percentage of time where that glare would be noticeable is less than 5%, which is acceptable according to LEED 4.1.

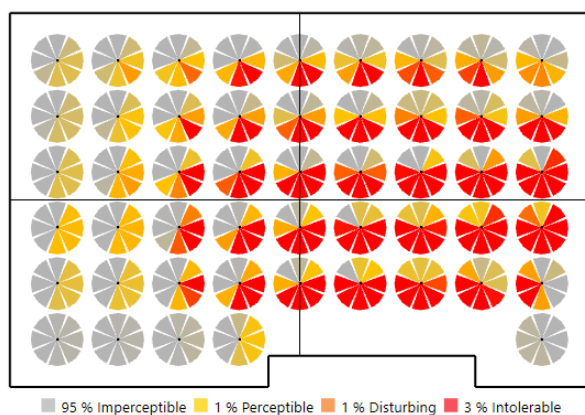


Figure 11: Results of the annual DGP analysis

Electricity production assessment

Electricity production results are provided on Fig. 12. In total the building produces 3451 kWh annually from PV. Those results show that the PV installation on the roof produces more electricity than consumed by the building, which is 1466 kWh annually, which characterizes it as a plus energy building.

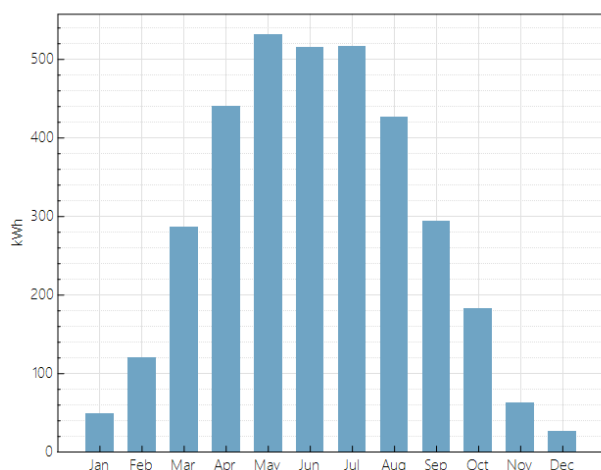


Figure 12: Results of the annual PV production

Discussion

According to the simulations conducted in this research, the Z free home should be moisture safe for ten years. In most of the layers there is a high mould index for the first few years, however, when that moisture dries, the mould index in all layers drops to values below 0.5. During the construction phase, it's important to make sure that the airtight layer is continuous. Wooden studs in the insulation frame should be positioned in a staggered order to avoid additional thermal bridges in the external wall. On the façade, capillary gaps and drip edges should be implemented, with air seals to avoid the penetration of additional moisture. Drainage cavities should also be

installed to allow rain to properly drain away from the building. Moreover, flashing on the façade should overlap on the joints, to prevent additional moisture from penetrating the façade.

The modelled building was tightly insulated to ensure the building's envelope maintained good thermal properties. The use of three passive systems – a Trombe wall, green wall, and Earth Air Heat Exchanger (EAHE) – was a main factor in reducing the need for cooling and heating. The simulation tools used were unable to simulate the accurate interaction of the performance of the Trombe wall and the green wall together with the EAHE. Thus, following this simulation phase, more extensive simulation is needed for more accurate results. More specialised software not used in the simulations carried out during this study, such as Ansys and TRNSYS, will be targeted for use in further studies.

The Z free home, as designed in this study, complies with passive housing requirements in terms of energy consumption. Energy was used for lighting, domestic hot water, heating, and ventilation, and amounted to 73.28 kWh/m² annually, compared to the requirement for multifamily houses, presented in table 9.2a of BBR (BFS 2017:6), of 75 kWh/m² annually. Using less than 15 kWh/m² annually, the building also fulfils heating and cooling load requirements. This can be attributed to the variety of measures including the earth air heat exchanger implemented in the building.

PV panels were simulated to produce 3451 kWh annually, which in theory, is enough to compensate for the energy needs of all domestic appliances, which amounted to 1341 kWh annually. However, it is important to consider that, due to the abundance of solar radiation during summer, and lack of solar radiation during winter, peak energy consumption occurs over winter, while peak energy production happens over summer. To compensate for this discrepancy, batteries are recommended to store energy for night- and winter-time consumption. It is also important to note that the proposed design of the PV panels does not take economic factors such as Swedish regulations and pricing in the field of renewable electricity production, into account.

The building has sufficient daylight access and is fully compliant with the EN 17037 and Miljöbyggnad requirements, yielding 3 credits in LEED 4.1. The annual DGP analysis shows a high percentage of views have a glare, but this glare can be reduced through the inclusion of interior shading devices. Moreover, the biggest issues with glare occur during between 11:00 and 14:00, during which time the building will likely be unoccupied, since it is meant for residential use.

Conclusions

The Z free home with its 9 zero targets is an experimental project for resilient and climate responsive living. In this paper, outcomes from a simulation of the building's performance are shown and discussed. The house's building envelope is moisture safe, provides adequate sunlight, offers good thermal performance, and performs as a plus energy building. Nevertheless, the researchers behind this study intend to reduce heating and cooling loads even more. This will require further investigation into building optimization and a detailed simulation of the passive heating systems used. Several levels and layers of rectification and optimization will be needed to enhance the building's passive heating and cooling systems and reduce operating costs. Given the increasing energy prices in Sweden and around the world, the use of passive systems, and renewables is becoming essential. Further life cycle analyses and life cycle cost and carbon sequestration calculations are to be carried out as the next phase of research before the physical implementation of the proof-of-concept house prototype.

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