Solar Passive House Concept and Thermal System Design

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This aricle puts forward a concept of family home enclosed in a greenhouse. Inspired by Naturhus and Earthship ideas, it leverages thermofluid technologies inspired by nuclear power passive cooling systems.

Bearing in mind serious threats posed by the climate change, in this largely due to modern architecture and construction, we have come to a point where all efforts need to be combined to promote green transition into more ecological footprint[1].

As a result, contemporary architecture has to search for new solutions to ensure steady and uninterrupted supply of power, water, heat and sewage services. Such need of innovative concepts combined with technological advancements release creative designs from restraints but come at the cost of dependence on a centralised, single-point-of-failure system. As the runaway climate challenges continuous supplies of resources, the concept of solar passive house leverages interdisciplinary technological breakthroughs, proposing a distributed, resilient approach to residential livelihood, relying on the building's topology as a vehicle for harvesting energy in a novel aesthetic form.

Because single-family houses take up a large share of residential development in Poland, they have been selected for the research to find out if they could be successfully adapted to the concept of Solar Passive Houses. Easier and more cost-efficient construction of a model solar passive house further underlay selection of single-family houses for the research. The planned studies will verify the effectiveness of the applied technology and opportunities of its widespread use in prefabricated panel systems[2].

The fact that solar passive architecture is not yet popular and that there are only a few solar passive one-family houses in Poland (e.g. earthship houses) gives rise to a number of research questions related to their design and construction[3]. Even if the passive house trends seem to be gaining momentum, solar passive architecture is still an innovative concept. Solar passive houses take advantage of architectural design in order to ensure maximum intake of solar energy, its optimal storage and distribution within the building. If a house can use up solar energy for all its energy needs without reliance on any external energy sources, it meets the criteria of a solar passive system [4].

The authors hereof have, thus, decided to focus their research on this innovative type of construction and its potential. The main goal was to design and erect a one-family building on the basis of an assumption that its heating would derive solely from solar energy and then study its performance. We have based our concept and research on the key feature: the system of distribution of heating and cooling. Our intention was to use data from experimental works on nuclear reactors for the purpose.

Preliminary thermodynamics calculations and analyses of similar solar passive facilities, constructed mainly in Scandinavia (e.g. naturhus)[4] have allowed us to conclude that in winter, the house will consume zero or only minimum energy for heating purposes, even on days when the temperature reaches extreme values +39.5ºC and –28.6ºC (extreme temperatures recorded in Poland) [6, 7]. We have found out that cooling in summer will pose a challenge, therefore we looked for cooling ideas applied in nuclear reactors.

Architectural science follows two development trends, either the traditional mode of internal development within its scientific discipline, or the interdisciplinary mode focused on creative design and synergy of research, interdisciplinary and hybrid studies, which goes beyond the boundaries of architecture [8].

At present, the authors hereof are at the stage of design research. Relying on the studies made so far, they have come up with a conceptual design of the solar passive building.

The preliminary stage of the research (pre-design stage) focused on the analysis of technology and problem solutions commonly applied in architectural design[5].

The stage of design research (design stage) is based on problem solutions commonly applied in architectural design and on selected research techniques[6].

Studies of thermodynamics with reference to possible application of experimental works on nuclear reactors in housing are now subject to 1D model multiphysics simulations, driven by fast prototyping, yet, their calculation results will not be discussed herein.

Field-specific literature

Our theoretical and design research derived from the concept of passive architecture, in particular solar passive architecture, and two types of buildings adhering to the concept have been identified, namely earthship and naturhus buildings.

Passive construction, in the form known today, was worked up and popularised by Wolfgang Feist, who – in 1996 – founded the first Passivehause Institute, an independent research institute. Over the time, such terms as a passive building and an energy-efficient building have entered the construction terminology[7]. Relevant standards have been adopted in reference to construction of this type of houses [10].

The author himself so describes the energy concept:

"A passive house is characterised with extremely low consumption of heat energy (kWh/m2/year). Passive heat sources ensure the thermal comfort inside the house, such sources include: human occupants, household appliances and the heat recovered from the ventilation system, air recuperation, sun, etc." Thus, the entire philosophy of a passive house assumes rational and optimal energy intake and use, which is next recovered and reused [12].

In their book, D.A. Brainbridge and K. Haggard discuss the term "passive architecture" that once generally contained all types of green housing and sustainable development in the built environment" [13].

The "solar passive architecture" trend developed in the 20th century alongside "passive architecture" concepts, yet its origin may be derived from Ancient Greece, Rome or China because certain elements had already been in use even before the introduction of mechanical heating and cooling in construction [14].

Solar Passive Architecture (SPA) uses solar energy to heat and convection cool the building[8]. The system is extremely easy to use and does not require any major mechanical and power devices such as pumps, fans or power control devices. Owing to construction materials, heat from sun rays can be reflected, transferred or absorbed for the purpose of collection, storage and redistribution of energy. Moreover, heat generated by the sun stimulates air movements that can be also controlled. SPA concept is based on assurance of thermal comfort in summer and in winter, for that purpose it starts with an analysis of the location, climate, shading and winds; the data will then underlie the selection of suitable construction materials and the design of proper ventilation system. As per the fundamental principle of SPA, the glazed façade shall be south oriented (within 30° of south at the maximum) and – in the morning and afternoon hours of the heating season – shall be fully exposed to the low on the horizon winter sun (any roller shutters shall be fully open) so that the sun can freely penetrate inside the building. The SPA concept conditions the size of the glazed façade on the range of factual winter temperatures, building size and thermal mass[9]. Thermal mass can be used for heating and cooling the rooms. In summer heat gains need to be controlled to avoid overheating. This is typically attained by shadowing, e.g. roller shutters or roof overhangs. There are two types of passive solar heating concepts with direct and indirect heat gain[10] (Tromble walls[11], sunspace – greenhouse[12]) [13, 16, 17, 18].

There are many examples of buildings constructed following the principles of SPA, mainly in the USA [19]. Whereas, the building of the Mont-Cenis Academy, built in 1999 in Germany, can be named here as a European example.

The Earthship [20] is a radical concept of an entirely self-built housing unit, made of recycled or upcycled materials, even car tyres. It is meant to be entirely autonomous, relying on energy and rainwater harvesting as well as on the use of greywater for the indoor plants watering and on the blackwater processing plant. The shape and topology of an Earthship is driven by the site location and its climate, with the prospect of maximising the solar gain in winter and minimising it in summer.

Naturhus [5], a conventional home wrapped within a greenhouse, was proposed by Bengt Warne in 1976. His villa in Stockholm introduced a gradient of living conditions between classical indoor and outdoor environments. This blend of inside and outside has rendered bright and open space living environment in proximity with nature, which has translated into the quality of life of the house dwellers.

There are several dozen of this type of buildings in the world, mainly in Scandinavia and Germany, but they are becoming more and more popular.

"According to the concept, a house of nature is a building that cooperates with nature and its cycles, that enriches the lives of its inhabitants, that is neither destructive nor poisoning. It is a house that borrows resources from nature and returns them. What we have used can be reused" [5].

Thus, the house – as per assumption – is meant to be a self-sufficient house model that reduces heat consumption in winter, that is provided with photovoltaic panels and offers greywater recycling.

Architectural Concept

Key aspects that need to be considered at the construction of a Solar Passive House (SPH), as per guidance found in literary sources, are its location, surface area, geometry as well as the lot proportions and orientation on the cardinal directions.

The authors of this paper have designed an L_SPH (Large_Solar Passive House) building, of a development area of 240 m^2, that may require a land lot of a surface area of approx. 2,000 m^2 at the minimum, depending on the terrain shape and orientation on the cardinal directions. Nonetheless, the technology does not restrict in any way construction of houses on different lot sizes, in different locations or construction of very small housing units.

The building has been designed based on the East-West axis. Reduced ratio of surface to volume constituted an important part of the concept as it would result in lower heat losses[13].

The residential part of the L_SPH house has been designed to be encased within a greenhouse, with glazed windows facing south. Such optimal exposure to the sun will ensure maximum heat gain from the solar energy. At the same time, the green embankment has been envisaged as smoothly extending into the natural terrain towards the north.

To maximise the heat accumulation effect, the building form strictly conforms ▶

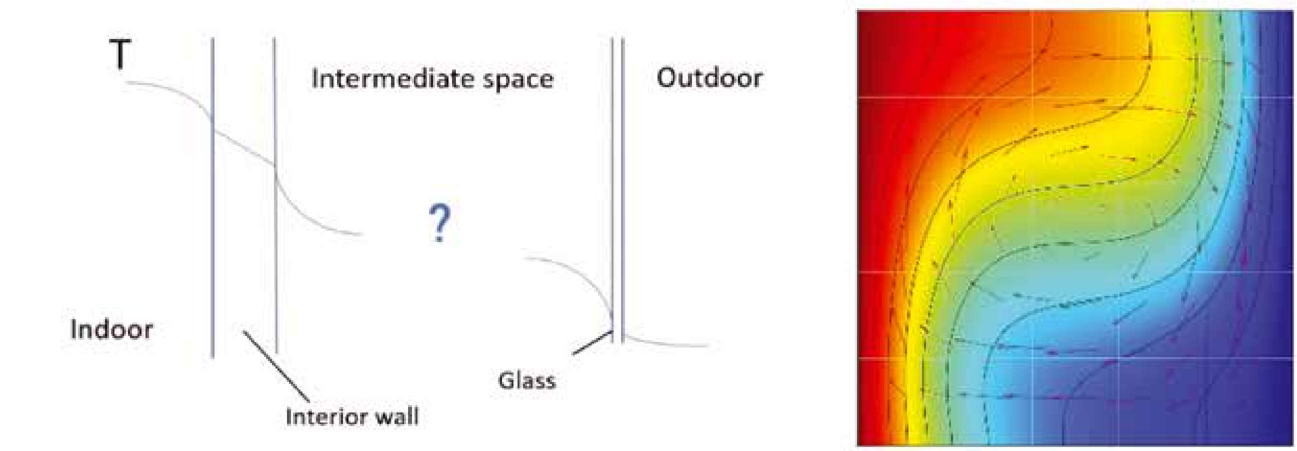

Fig. 1. Fourier's Law approximation of the heat transfer from the indoor to the outdoor. By building a layer of calm air, we can ensure that the extended air gap between the non-insulated interior wall and layer of glass works as an insulator. However, the buoyancy effect of the thermal gradient in a wide cavity is very difficult to be reliably computed – graphics on the left elaborated by the authors, graphics on the right derives from a data source [24, 25]

to topography. The view of the surrounding landscape from the glass elevation on the south side, combined with transparency of the greenhouse zone of an orangery (also accessible in winter), integrate the indoor and outdoor zones in the summertime, blurring any visible borderlines between them. The greenhouse zone will also ensure a heat buffer with optimum microclimate parameters for the minimum energy consumption.

Designed technology is also suitable for solar passive houses located on flat terrain, typically found in the region of Wielkopolska (Greater Poland). Moreover, under the concept of a solar passive house, the land lot exposure to the south should be clear of any coniferous trees or any other obstacles [21].

The rooms orientation should lead the occupants along the Sun's path in their daily activities. Therefore, a study room has been designed from the east side and bedrooms – from the west side, with the living room zone and the fireplace located in the central part. Overhangs which protect relevant building walls against exposure to summer peak sun position are to safeguard these rooms against overheating.

Another issue to be considered with the optimum house energy performance in mind is whether or not to provide the house wrapped within the greenhouse space with any additional devices.

Rooms that do not require natural light such as cloakrooms, bathrooms and service rooms for relevant wiring and piping systems have been envisaged in the underground part, which also serves as a heat buffer. This way, the potential of daily accumulation of heat in the greenhouse and the potential of natural thermal insulation of the overground part of the house can be harnessed to improve the house performance. It can be further supported with solar thermal collectors[14] and the fireplace with a water jacket (additional energy sources). The water jacket is to be connected to the system of water tanks that pumps and circulates water in the house to heat it. A ground-coupled heat exchanger intended to capture and dissipate heat or to cool the air down makes an integral part of the system.

In summer hot air is discharged from the greenhouse space via a solar chimney and cold air is blown in from the water tank buffer zone. Water tanks near the glass elevation of the greenhouse space will facilitate the cooling effect and contribute to biodiversity. Moreover, the treated house greywater collected in tanks and water from soakaway drains or deep water wells will be purified and aerated by shoreline plants. The compost bin for organic waste is also envisaged in the design.

All these elements are, to a lesser or greater extent, already used in construction, however, the core of the research project and the main research question pertains to the heating and cooling distribution system achieved by water tanks. The idea stems from experimental works on nuclear reactors.

Technology

The key innovation of a Solar Passive House is not any particular piece of engineering, but the entire house topology and how it integrates various functions to retain thermal comfort inside the building.

The house wrapped within a greenhouse space serves two main roles: firstly, it traps the radiation of the sun within – a classical greenhouse effect, but secondly, it provides a layer of insulation between the actual house and the elements of the greenhouse. The main technological challenge here is the lack of norms or established computational methodologies [23], that would allow precise computation of thermal properties of this type of house design. Figure 1 compares the thermal gradient of a traditional, single-walled and a solar passive house.

The notion of harvesting solar thermal energy to the comfort of the inhabitants has been studied thoroughly [13]. The studies have emphasised the importance of Sun's changing position throughout the year. Another obligatory part of the concept is the thermal buffer. Its role is to retain energy for the night. This function will be achieved by relying on stones or mostly water as heat storage.

Heat capacity of water is two times the heat capacity of concrete and three times the capacity of a masonry wall [17], thus, it makes up an ideal heating and cooling storage.

Thermal systems that rely on natural phenomena to drive and control the heat transfer are the underlying concept of nuclear safety systems. Under any circumstances, the reactor core must remain cool. Notably, the Westinghouse AP-1000 reactor (AP standing for Advanced Passive) boasts an entirely passive (pump-free) core cooling system that has no moving parts needed to bring reactor to a safe, cool state [26].

At the heart of Solar Passive House is the energy storage system, coming in the form of a large water tank, equipped with a heat storage heat exchanger (HS). The HS loop, along with other heat exchangers, including solar thermal heat collector, under-floor piping, heat-sink, and auxiliary heat source, all feed to the control panel, where thermal system configuration of the house can be fine-tuned to respond to the environmental conditions. The components of the system are presented in Fig 2. Additional thermofluid loops include heat exchangers coupled with: thermal storage tank, aquaponic tank, floor heating, evaporative cooler, auxiliary heater, hot tap-water tank and solar thermal collector. WP stands for water purification unit.

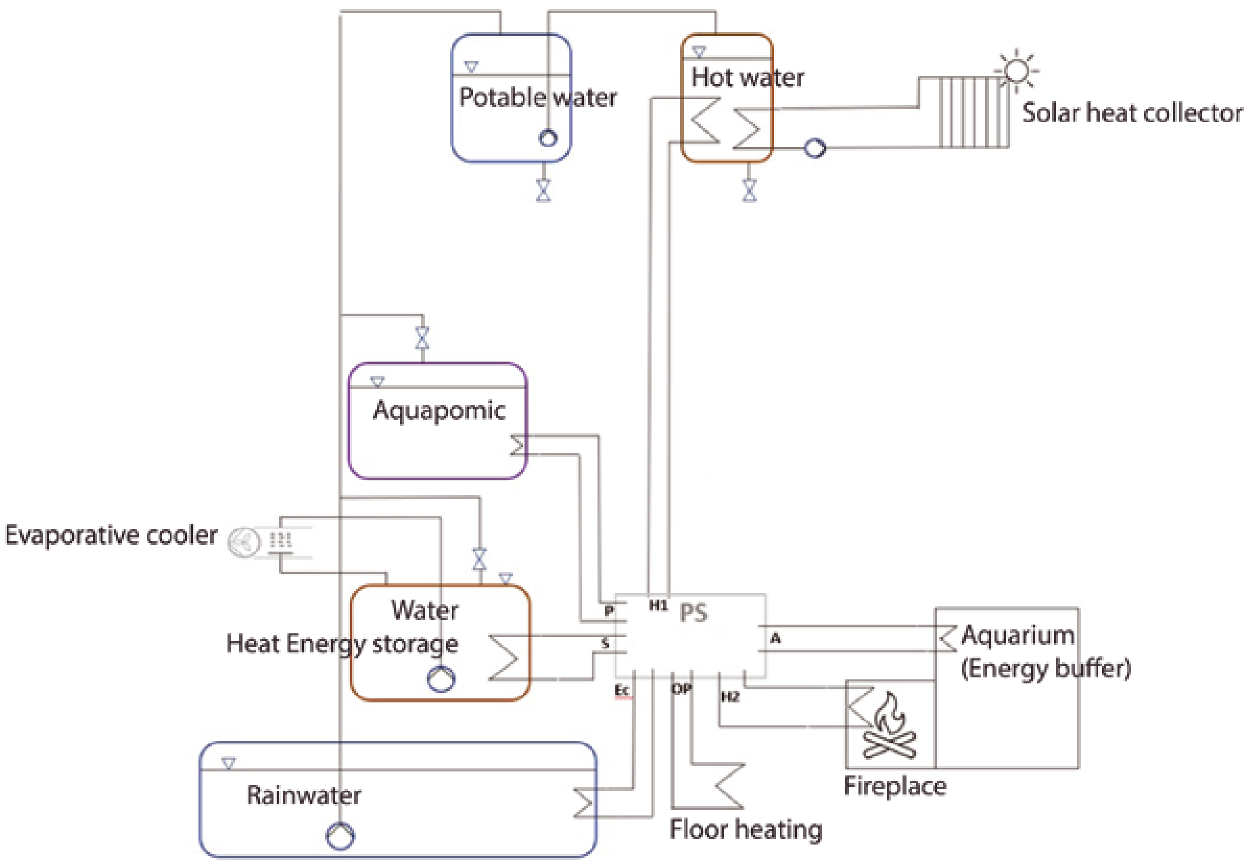

Fig. 2. Thermal hydraulic energy management system

The Water Heat Energy storage tank is placed at the heart of the house, as a thermal buffer. Surrounded by multiple heat exchangers, collectors and dissipators, the control panel serves to match the thermal system topology to the current weather conditions. Multiple components play various roles: an aquaponic rooftop installation – is a solar thermal collector, aquarium – a living room heat dissipator, rainwater tank serves as means of emergency – graphics elaborated by the authors

The extreme thermal conditions to be withstood are peak of winter and peak of summer conditions. While generation of the auxiliary heat in winter can rely on very traditional methods, the main challenge is to dissipate the immense heat harvested in the peak of summer. The cooling system relies on the following passive mechanisms, visualised in Figure 2 below:

- Solar chimney after-heater – placed in the hottest place of the house – at the top of the sunspace (greenhouse), this device further increases the air temperature using solar radiation, to generate a buoyancy effect [27] that pumps the air out. The solar chimney can also be reversed to work as an air heater in winter.
- Intake air pre-cooling via air-water heat exchanger, dumping the heat into an outdoor body of water. This air intake does not operate in winter.
- Evaporative water cooling – the heat sink loop mentioned above relies on an outdoor water evaporation unit. It works at night to evacuate the heat harvested during the day.

Future work will focus on development of the engineering design methodology of reliable sizing and control of the thermal system. It will focus on identification of mathematical correlations that will allow us to predict response of this complex system to the varying environmental conditions.

Conclusions – benefits and drawbacks of living in a Solar Passive House

Eathship houses by Michael Reynold are commonly criticised for thrash used in their construction, e.g. tyres or cans, as well as their poor aesthetics. Critical voices have appeared also in Polish publications, nonetheless, alongside criticism of Michael Reynold's concept, they have praised Balcomb House, built in 1979 by William Lumpkin, a pioneer of solar architecture (an example of solar passive architecture) [28]. Another example of positively assessed SPA is Mont-Cenis Academy in Germany by Jourda & Perraudin, constructed in 1999 [16].

Naturhus type of buildings were generally rated higher due to better aesthetics, green space in the greenhouse and lower temperature difference between the inside and outside of the building.

Scientific publications also refer to cases when solar passive building met positive reaction, even if they have been located in extreme Swedish climate:

„Between 1976 and 1981 the Nature House. Although the most extreme temperatures recorded outdoor during the research period were – 29°C and +34°C, the greenhouse never became cooler than 0°C or warmer than +27°C due to heat storage effect of ground and ventilation system" [29].

Difficulties in shading the entire greenhouse space (residential space protected with shading elements such as awning, roller shutters, sun shade sails, etc.), lack of privacy in that zone, insects in the greenhouse space and problems with cleaning the glazed façade were seen as the major drawbacks of the Nature House building types.

No Nature House building type has as yet been built in Poland.

The already designed SolarPassive building, despite the fact that it derives from highly

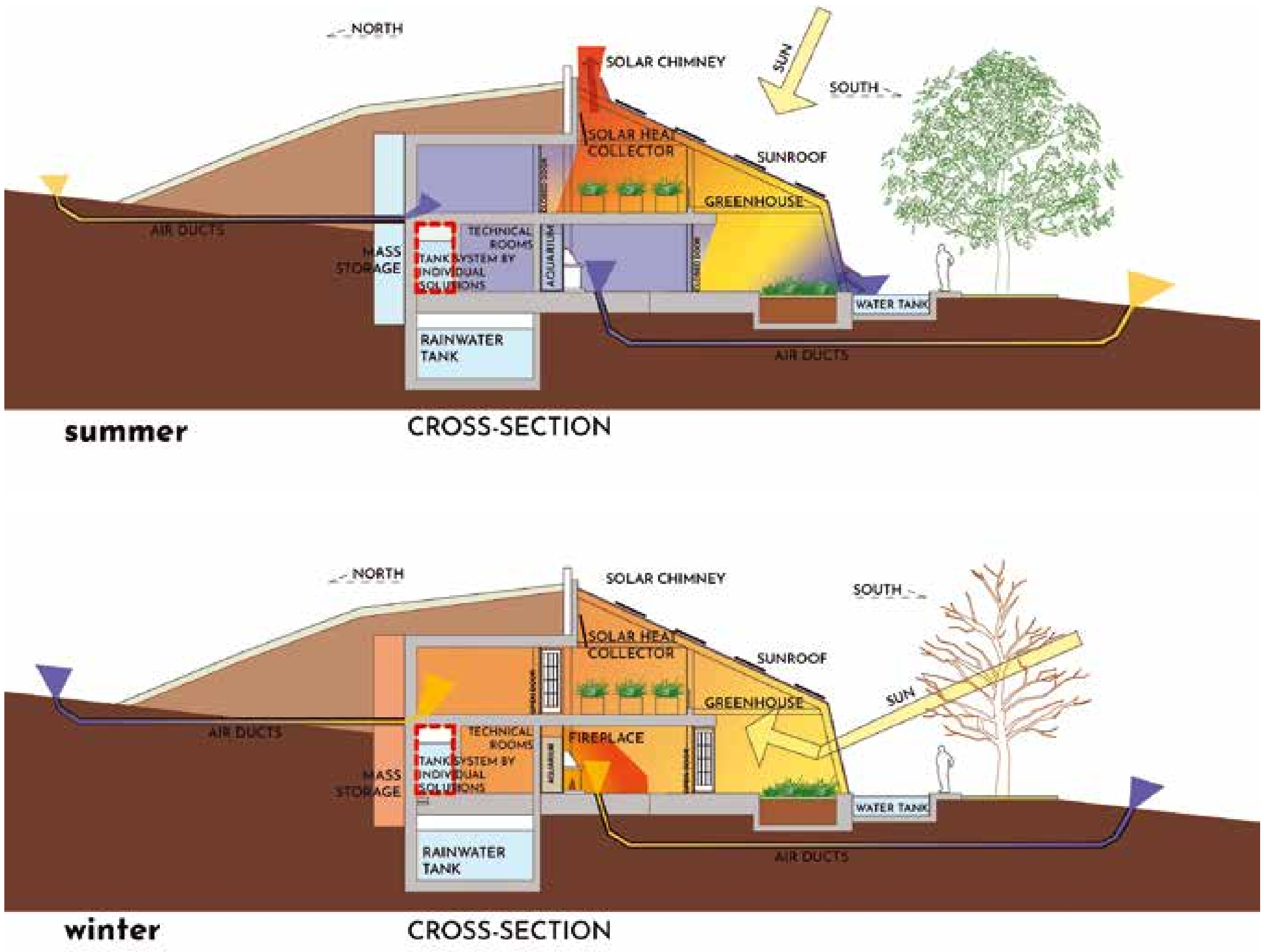

Fig. 3. The house architecture operating as a whole, during the summer and winter extreme thermal loads – elaborated by the authors

rated concepts, is not free of drawbacks such as insects in the greenhouse space, problems with cleaning the glazed façade and difficulties in efficient use of solar energy. It shall be highlighted that solar energy cannot be encapsulated within limits of mathematical formulas, which contributes to complexity of relevant calculations. Solar energy is also susceptible to weather conditions such as the wind, humidity and air pollution (dust in particular).

Calibration difficulties in the designed technology impede options of designing easily adjustable systems. Another unpredictable factor is the imbalance between energy demand and supply.

Certain works have been undertaken to design a heating and cooling distribution system with the observance of the principle of communicating water tanks. The concept is based on experiments with heat transfer in core reactors and stands a chance to benefit from the synergy of the already existing technologies and concepts of solar passive houses.

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Fig. 4. Exterior and interior views – elaborated by the authors

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PRAWIDŁOWY SPOSÓB CYTOWANIA
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ABSTRACT:
This aricle puts forward a concept of family home enclosed in a greenhouse. Inspired by Naturhus and Earthship ideas, it leverages thermofluid technologies inspired by nuclear power passive cooling systems. The solar gain of the greenhouse allows for enhanced heating fuel efficiency in winter, while a system of solar-drive heat exchangers dissipates excess heat in summer. This general living qualities of such innovative housing concepts are discussed, followed by an outline of the computational challenges that need to be overcome by experiment-driven modelling, aiming for the demonstrator that successfully controls summer daily temperature peaks.

KEYWORDS:
solar passive architecture, net-zero, energy, ecological houses, greenhouse

STRESZCZENIE:
KONCEPT DOMU PASYWNEGO SŁONECZNIE I PROJEKT INSTALACJI CIEPLNEJ. W artykule przedstawiono koncepcję domu jednorodzinnego zamkniętego w szklarni. Zainspirowany pomysłami Naturhus i Earthship, wykorzystuje technologie termofluidów inspirowane pasywnymi systemami chłodzenia energii jądrowej. Zyski słoneczne w szklarni pozwalają na większą efektywność wykorzystania paliwa do ogrzewania w zimie, podczas gdy system wymienników ciepła napędzanych energią słoneczną rozprasza nadmiar ciepła latem. Omówiono ogólne cechy użytkowe takich innowacyjnych koncepcji mieszkaniowych, po czym przedstawiono zarys wyzwań obliczeniowych, które należy pokonać w drodze modelowania opartego na eksperymentach, w celu stworzenia demonstratora, który skutecznie kontroluje dzienne szczyty temperatur w lecie.

SŁOWA KLUCZOWE:
architektura pasywna słonecznie, zeroemisyjne domy, energetyka, domy ekologiczne, domy w szklarni

[1] According to prudent estimates, the construction sector itself generates about 30–40% of CO_2 emissions, whereas, construction and building occupancy combined consume about 40–50% of total generated energy. Urbanised areas use up 75% of natural resources and emit from 60 to 80% of total greenhouse gases [1].

[2] Prefabricated construction is a method of construction that consists in most or all components being made off-site, most often in specialised production halls [2].

[3] From the collected information, it follows that in Poland there are at most 6 earthship houses, the first was erected in Mierzeszyn near Pruszcz Gdański, in Pomerania. Private house [3].

[4] According to the authors of the book Naturhus, there are 8 completed nature houses of this type in Sweden and several more are under construction, there are additional 3 in Scandinavia, and 20 in the world [5].

[5] In accordance with the article „Architektura-badania poprzez projektowanie", table 3, the stage included application of such research techniques as collection of documentation, analysis of legal acts, map and base-map analysis, comparative analysis, site visitation, taking photographic documentation, sketching, observing, researching correlations between historical facts, social facts and trends in the development of architecture, interpretations, explanations, studies of literary sources and case study [9].

[6] In accordance with the article „Architektura-badania poprzez projektowanie", table 3, the stage includes research techniques such as brainstorming, qualitative survey, case study, SWOT analysis, analogy, comparison, convergence, divergent thinking [9].

[7] A passive building has been defined as a building attaining a rigorous level of energy efficiency as heat demand (at the level of ≤15kWh/m^2/year), and an energy efficient building – as a building characterised with heat demand at the level of ≤70kWh/m^2/year. Standard heat energy requirement per house in Poland ranges from 90 to 120 kWh/m^2/year. A Zero-Energy Building (ZEB) is a building with net zero heat energy consumption [11].

[8] Convection cooling – is a passive cooling method relying on the natural phenomenon of heat transfer to reduce the heat gain in buildings [15].

[9] Thermal mass – non-thermally insulated elements of the building, characterised with high specific heat and high volume density, have the ability to serve the role of thermal mass [16].

[10] Indirect gain – concerns solutions that convert energy generated from sun rays into heat energy in a separated space and the so gained heat is next distributed within the building by way of heat transfer phenomenon (convection) [16].

[11] Tromble wall – type of an external wall that indirectly gains energy using thermal mass, e.g. massive wall separated from the outside by glazing and an air cavity. The wall has no internal thermal insulation and is painted black [17].

[12] Captured heat gain – thermally insulated space, e.g. by building an extension with greenhouse space [16].

[13] The overall house shape predetermines heat exchange with the surroundings. To reduce heat losses, the ratio of the surface to volume needs to be decreased as much as possible [21].

[14] Efficiency of collectors installed on the green roof will be improved by 3-5% and their useful life will be extended. The design envisages rotated photovoltaic panels and monitoring of the technical condition of collectors. Collectors of decreased efficiency can be recycled as chargers of external lighting, garden power tools or garden water pumps [22].