Energy-efficient solutions for buildings on thermal design basis

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Abstract. Buildings consume energy at different levels at every stage of life cycle. Approximately half of all nonrenewable resources (water, energy, and raw materials) the mankind consumes are used in construction. Modern human civilization depends on buildings and what they contain for its continued existence, and yet our planet cannot support the current level of resource consumption associated with them. This subject is relevant especially in the context of solving the issues of designing residential buildings, in particular on the basis of thermal design, which this article reveals in detail. The article describes methods of energy-efficient design of buildings. This paper justifies how energy-efficient principles and methods of building design can be incorporated into the proposed construction design and the benefits that can be used in building design.

1. Introduction
The energy is one of the most important catalysts in the creation of wealth, economic growth and social development for all countries. Buildings have considerable share in overall world’s energy consumption. Therefore, they have a profound impact on the environment. The energy is used on each stage of the building life-cycle. It includes: area selection, architectural design, structural systems and material selection, building construction, maintenance and use of the buildings, demolition, reuse and waste management. According to the World watch Institute buildings account for 40% of world’s energy annual consumption. Building’s energy consumption can be significantly reduced on each life cycle stage of the building. In this study we have explored energy-efficient methods of life-cycle construction. In this context we are giving the information about building life-cycle and we are explaining energy efficient guidelines at all stages of the life cycle [1,2].

The Passive House Principles, including thermal mass, outside shading, orientation of a building, cross ventilation and better insulation in the buildings can reduce usage of the energy for maintaining comfortable internal temperatures. The use of renewable sources of energy reduces the exposure of building on the environment. Smart design of the building diminishes energy consumption, saves money and decreases the effect on the climate change. On the other hand, poorly designed buildings are uneconomical and result in greenhouse gases emissions [3,4].

Energy consumption per square meter is more than 3 times higher in Ukraine comparing with Germany, for instance. On average, resident of Germany uses \(90\,kW\cdot h\) on one square meter per year, while resident of Ukraine - up to \(300\,kW\cdot h\). No wonder, because most of Ukrainian households regulate the temperature in the apartment by airing the room. A total of 80% of Ukrainians pay for heating due to square footages of their apartments, not for real consumption [5].
The statistics on country’s energy consumption shows that Ukraine is on the 3rd place in the world by the amount of energy consumption (figure 1). The energy consumption per capita for Ukraine accounts for 84 MJ per year. It is the biggest rate in the world - Ukraine is on the first place in this rating. For Ukraine such indicator demonstrates that the country consumes energy excessively [4,6,7]. Consequently, there are no doubts in the relevance of establishing building constructions with usage of environmentally friendly and renewable sources of energy. It can be achieved in contemporary architecture and construction. Ways to achieve it are: improving architectural and planning solutions; using external constructions with necessary level of thermal protection for building envelope; implementation of efficient microclimate and energy saving systems in buildings; usage of renewable sources of energy; quality improvement of building design. The transition to such type of buildings can significantly decrease fuel and energy consumption, lower the costs of the energy and reduce greenhouse gas emissions [8-10].

2. Methods for ensuring energy efficiency in buildings

2.1. Town-planning methods. The main measures in the Urban Development field are:

- absence or insufficient insolation;
- excessive insolation of the southern building facade;
- windbreak from prevailing wind side.

2.2. Space-planning methods:

- compactness of the house (the criteria of building shape’s energy efficiency is its compactness; it is represented by ratio of external envelope space of the building over its volume (S/V). Best shapes for energy-efficient house are spherical and cubical.
- functional zoning of the house (placing warm premises closer to southern part of the building, while utility rooms can be placed on the northern part) [11].

2.3. Engineering methods:

These methods include application of ventilation system with air recuperation. (Air recuperation - is a process when the cold intake air heats by exhaust hot air. The hot air in recuperative heat exchanger gives most of its heat to the intake air. Therefore, hot air doesn’t go out through the opened window useless). Also, these methods include laying underground channels for water and air heating or refrigeration. The natural concepts of wind ventilation are innovative alternatives to common mechanical ventilation systems for tall buildings. The new European Central Bank’s office building in Frankfurt (architects: Coop Himmelb, energy concept: Univ. Prof. Brian Cody) will be the first office building to use only natural ventilation. The building design is based on wind and rising forces around and inside the building. Additional solutions to reduce the energy consumption in a high-rise residential building by integrating the thermal building simulations during the design phase of a building as well as for renovation project is presented. The energy simulation software tools can be important for reducing the cost of energy in buildings [12,13].

The natural concepts of wind ventilation are innovative alternatives to common mechanical ventilation systems for tall buildings. A striking example of the application of the energy concept is the project of the new office building of the European Central Bank in Frankfurt (Figure1), which will be the first office building using only natural ventilation. The building design is based on wind and rising forces around and inside the building [14].
2.4. The isolation methods
Such methods include complete house thermal insulation to prevent cold joints: foundation, walls, roof, ceilings, window openings and doorways.

2.5. Constructive methods
Include the following measures:
- Absence of translucent parts on the northern building facade;
- Presence of translucent parts on the southern building facade;
- Arrangement of solar systems on the roofs and not just there.

By using all these methods significant losses of energy can be avoided:
- Thermal insulation of barrier constructions (walls, roof, ceiling and ceiling above basement) except windows - 15-25%;
- Thermal insulation of barrier constructions (walls, roof, ceiling and ceiling above basement) except windows - 10-15%;
- District heating substation modernization, including adjustment to the weather conditions and pump circulation - 10-30%;
- Comprehensive modernization of the internal district heating system. It includes installation of temperature control units on each heating appliance, pipelines thermal insulation - 10-25%.

3. Basic research and calculations
The development of the energy concept of building design and the analysis of the problems of the use of energy modernization in construction are reflected in the study [15].

The implementation of this study is carried in Kharkov - in the central part of the city (Moscowsky district).

Urban development conditions:
- The total land area: \( S = 2.8 \) ha.
- Planning scheme of the quarter - group housing.
- There are residential and commercial buildings and structures on the quarter territory, their height ranges from 1 to 10 floors.

It was suggested to knock down the old construction. The residential building is oriented in the direction towards north - south (Figure 2).

The effective (passive) method of preserving heat obtained from solar radiation and internal heat sources is to establish massive accumulating elements of a building (interior space) [16-18]. The 10-storey energy-efficient house is a single-section frame 45-apartment building (Figure 3).
Figure 2. Urban development solution: master plan and 3D model space of a residential quarter.

Figure 3. The architectural design of the Passive House.
Southern facade – Tromb-Michel wall, which is a dark colored wall made from material with high thermal capacity. It complies with Passive House standard in all aspects.

The architectural design was developed in accordance to the SCN 2.2.9-2009 requirements - building proportions resemble a square depending on the house compactness [19].

For complete energy-efficient residential building design a number of thermal comfort studies were held together with studies related to energy-efficiency increase, in particular, in the residential tall building in Kharkov.

4. Thermal engineering calculation of barrier structures
The purpose of Thermal engineering calculation is a measurement of resistance to the heat transfer $R$, together with the thickness of heated barrier layers. Under these circumstances, assigned temperature conditions is ensured in the premises of the building, taking into account desired economic indicators. The calculations are performed in accordance with SCN B.2.6-31: 2016 requirements - Thermal insulation of buildings.

For thermal engineering calculation we have chosen multi-layered construction scheme of exterior wall, and main thermophysical indicators of building materials. These indicators should be applied in the design of energy-efficient residential building.

Output data (Kharkov) [20]:

- $t$ - estimated winter temperature of the five coldest days per week (exceedance probability) 0.92;
- $t = -23^\circ C$;
- $t_2$ - estimated temperature of the coldest day (exceedance probability) 0.92; $t_2 = -28^\circ C$;
- $t_3$ - average temperature of 3 coldest days; $t_3 = -11^\circ C$.
- Average wind speed - 6.1 m / s .
- Humidity area - dry.
- The number of degrees/ a day of heating season - 3799.
- Temperature zone according to the temperature zoning map of Ukraine - I.
- Air humidity in residential building premises - normal. ($\varphi = 50-60\%$), therefore, according with SCN B.2.6-31: 2006 we take the facility operating conditions - A.

In accordance with the SCN B.2.6-31: 2016 requirements – “Thermal insulation of buildings” [19] - in order to examine the health and sanitary standards implementation, we calculate required resistance to the heat transfer using the following equation (1):

$$ R_0^{req} = \frac{t_{int} \cdot t_{ext}}{\Delta t^n \cdot \alpha_{int}} n $$

where $t_{int}$ is a heated premises distinctive temperature; we take 18 °C; $t_{ext}$ - external air temperature of the five coldest days per week, °C, is taken according to the DSTU-N B V.1.1-27: 2010 [20]; $n$ - the coefficient, whose value depends on the barrier exterior surface position towards outdoor air, $n = 1$ (according to SCN B.2.6-31: 2006); $\Delta t^n$ - normative temperature fluctuations between indoor air temperature and internal barrier surface temperature; for residential houses walls $\Delta t = 6^\circ C$; $\alpha_{int}$ - heat transfer coefficient of the internal wall surface, $\alpha_{int} = 8.7 \frac{W}{sq.m. \ ^\circ C}$

$$ R_0^{req} = \frac{18 \cdot (-23)}{6 \cdot 8.7} \cdot 1 = 0.61 \left( \frac{sq.m. \ ^\circ C}{W} \right) $$

The actual resistance to the exterior wall heat transfer is determined using the following equation:
\[ R_0 = R_{int} + R_1 + R_2 + R_{ext} \left( \frac{sq.m\cdot^\circ C}{W} \right) \] or \[ R_0 = \frac{1}{\alpha_{int}} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{1}{\alpha_{ext}} \] (3)

where \( \alpha \) - heat transfer coefficient of the external wall surface, \( \alpha_{ext} = 23 \frac{W}{sq.m\cdot^\circ C} \).

In a constructive spirit we increase the clay brick wall thickness of the standard size - 0.51m and recalculate \( R \) value:

\[ R = \frac{0.114 + 0.03 + 0.51}{0.76 + 0.043} = 0.887 \left( \frac{sq.m\cdot^\circ C}{W} \right) \] (4)

The normative heat transfer value for external wall with reconstruction for I zone \( R = 2.2 \frac{sq.m\cdot^\circ C}{W} \). Since value \( R < R_n \), it is necessary to implement wall heat insulation. We take polystyrene foam insulation and define its thickness \( \delta = 0.110 \text{m} \). We have selected the most rational wall construction solutions in order to improve building energy-efficiency in accordance with European developments [17].

\[ R = \frac{0.884 + 0.110}{0.05} = 2.204 \left( \frac{sq.m\cdot^\circ C}{W} \right) \text{ then } K_w = \frac{1}{R} = 0.53 \left( \frac{W}{sq.m\cdot^\circ C} \right) \] (5)

Additionally, basing on the thermal comfort simulation in buildings and on the European experience [7,8], we have conducted building thermal imaging to identify the heating losses (Figure 3). The thermal imaging allows making evaluation of barrier constructions thermal insulating properties. The facade color indicates that the house insulation is made without cold joints. Cold joint is a basic structure element or a part which lets cold through itself [19].

To create an interesting architectural image of the building at the second stage it is possible to use thermal design methods. The energy simulation software tools can be important for reducing the cost of energy in buildings [9].

5. The main conclusion

Consequently, as a result of new building construction we have obtained the following results and values. As a result of the work, energy-efficient 10 story residential house was designed. This purpose was implemented by following the objectives:

- Different architectural, planning and dimensional solutions were applied; analysis of building impact on energy consumption was held with the help of such programmers as Autodesk Energy Analysis and Green Building Studio.
- Building barrier constructions were selected. Its values are the following:
  - exterior walls \( R_0 = 7.020 \frac{sq.m\cdot^\circ C}{W} \); roof \( R_0 = 7.035 \frac{sq.m\cdot^\circ C}{W} \);
  - glazing \( R_0 = 1.754 \frac{sq.m\cdot^\circ C}{W} \); ceilings \( R_0 = 3.537 \frac{sq.m\cdot^\circ C}{W} \); base plate \( R_0 = 5.42 \frac{sq.m\cdot^\circ C}{W} \).
- The ventilation with recuperation and heating was selected. Also, the equipment which uses renewable sources of energy was chosen. It allows reducing energy costs by \( 51.8 \frac{kW\cdot h}{sq.m} \) per year, in general.
Thermal building simulation is a powerful tool to assess the energy performance of a building. The simulation is recommended to be integrated during the design phase of a building. During this stage, there are more opportunities to influence the design of the building and to change the design as it is far cheaper to change the design rather than the real building. Moreover, various numbers of scenarios can be modelled in order to obtain the most optimum design, not only on the physical design, but also the operational scenario [12].

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