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MATHEMATICAL MODELS FOR DETERMINATION OF ENERGY NEED FOR HEATING

One of the key indicators that characterize efficient energy use for heating purpose is the specific value per unit area and/or volume. This paper is devoted to the study of various methods application features used to determine energy need for heating, which there are a large number [1].

Determination of energy need for heating based on experimental data has a number of approximations and inaccuracies, so it is advisable to establish the annual energy need for buildings based on the calculated approaches. Addressing these challenges requires the use of calculation methods and mathematical models. Till the recent years, the methods for determining energy consumption and energy efficiency assessment in Ukraine took into account only annual energy consumption for heating and did not take into account the need for cooling and hot water supply [2, 3]. According to standard [2], the building energy efficiency should be determined on the basis of calculated or actual annual energy consumption for heating needs, while ensuring appropriate sanitary and hygienic norms in the building spaces.

Most of the buildings in Ukraine belong to the mass construction of 1960-90s. For these buildings, specific heating and ventilation characteristics are determined depending on the purpose, year of construction and the volume of the building [4]. Even nowadays in Ukraine calculations are made according to the aggregated heating characteristics. There are also sectoral norms for energy need for heating depending on the purpose, volume and location of the object [5].

Standard [2] uses a more detailed method for energy consumption calculation on the basis of heating degree-days (HDD). The fixed heating period duration is necessary for calculating the total heat losses and gains during the heating period [2]. This method allows adjusting the heating energy consumption according to the actual outside air temperature and average temperatures in building spaces. But when considering the building as a complex energy system the needs for heating and cooling should be considered in order to maintain the set inside air temperature, also energy need for hot water supply, as well as energy sources should be taken into account. To replace the previously mentioned standards, national method of calculation is introduced [6, 7], which includes the estimation of energy need for heating, cooling, hot water supply and is based on definition of monthly indicators (quasi-stationary calculation method). Normative values of specific building energy consumption indicators are also revised, including the need for heating, cooling and hot water supply [7]. Quasi-stationary methods calculate the heat balance over a fairly long period of time (usually one month or a whole season), which allows taking into account the dynamic effects with the use of empirically determined heat gains/losses utilization coefficients.

Non-stationary models for energy consumption calculation are advisable to use for the detailed analysis of energy performance indicators. A large number of papers are devoted to the system analysis mathematical methods application for the study of buildings energy performance [8-10]. The approach of European standard [11] accepted in Ukraine is based on a simplified hourly method for calculating building energy consumption. Dynamic methods calculate the heat balance over short-term time periods (usually one hour) taking into account the amount of heat accumulated in or released from the buildings enclosures.

The standard [11] proposes five resistances, one capacity (5R1C) model, which allows implementing the model in a simplified three-node method. This approach requires the creating or use of existing programs for this method realization.

The energy need for heating is based on the calculation of the heating level for each hour to be delivered to the internal air temperature node to maintain a certain set-point temperature. The set-point temperature is an average weighted value of internal air temperature and radiant temperature. This scheme is implemented on the basis of standards EN 13790 and EN 13786 [11, 12].

An alternative option is to use existing software products for the dynamic models implementation, one of them is EnergyPlus [13]. The EnergyPlus software product (E+) is one of the most comprehensive open-access programs for building energy performance modeling. This program uses the best approaches of the two well-known programs DOE-2 and BLAST, the calculation methods of which are close to European standards [14]. In contrast to the above mentioned method, E+ separately takes into account the heat capacity of external and internal enclosures. In the simulation of heat fluxes through fenestration surfaces E+ uses a subroutine of Window 5 calculation [15], a Slab preprocessor program [16] is used for calculating the heat losses through the slab on grade.

The E+ software uses climatic data from the International Weather for Energy Calculation (IWEC) file as a typical year for the considered city [17]. For Ukraine territory two climatic IWEC files for Kiev and Odessa are created, which are averaged characteristics of each of two temperature zones.

Consequently, due to the fact that above-mentioned dynamic methods are only becoming widespread in Ukraine, the aim of the work is to compare the approaches for calculating the building energy need for heating when determining buildings energy efficiency indicators. Objectives:

1. Analysis of the features of using the meteorological data of the typical year and normative climatic data and other output data when applying different methods of determining the annual energy need for heating.
2. Determination of the annual energy need for heating by the aggregated, detailed quasi-stationary and non-stationary methods.
3. Creation of a quasi-stationary model using monthly approach according to the national calculation method of DSTU B.A.2.2-12: 2015 and determination of energy need for heating.
4. Creation of a non-stationary simplified hourly model based on EN 13790, EN 13786 and calculation of energy need for heating.
5. Calculation of energy need for heating in non-stationary mode on the basis of the created model in E+ software.
6. Comparison of the obtained results.

Input data

The research object is a room in the building of the 1970s mass construction. Room dimensions are 5.5×6.1 m, floor-to-ceiling height is 3.2 m. It has one exterior wall (5.5×3.2 m) with exterior window (5×2.5 m). The exterior wall has the thermal resistance R = 0.8 (m^2·K)/W (one-brick wall). The outer window is a double glazed system with wooden frame. Interior walls are built with half-brick (δ = 0.125 m). Ceiling and floor construction is reinforced concrete slab (δ = 0.2 m). Ventilation is natural; air exchange rate is 1 h^{-1}. The building is located in the city of Kiev. The design internal air temperature is 18°C. The heating system is ideal load air system. Solar heat gain coefficient of fenestration surfaces in the room is 0.56. This coefficient was calculated in the E+ program according to the type of glazing.

Hourly climatic data from IWEC file was used in the calculations, which include dry-bulb temperature, relative humidity, atmospheric pressure, wind speed and direction, direct and diffuse solar radiation etc. [17]. Figure 1 shows a graph of changes in the average monthly values of external air temperature and solar radiation on vertical surfaces, calculated on the basis of IWEC values [17] (marking: IWEC S, IWEC N) and the national calculating methodology DSTU B A.2.2-12: 2015 [6] (marking: S Normative climate data, N Normative climate data), also the values calculated by the E+ program on the IWEC database (marking: E+ S, E+ N) are given.

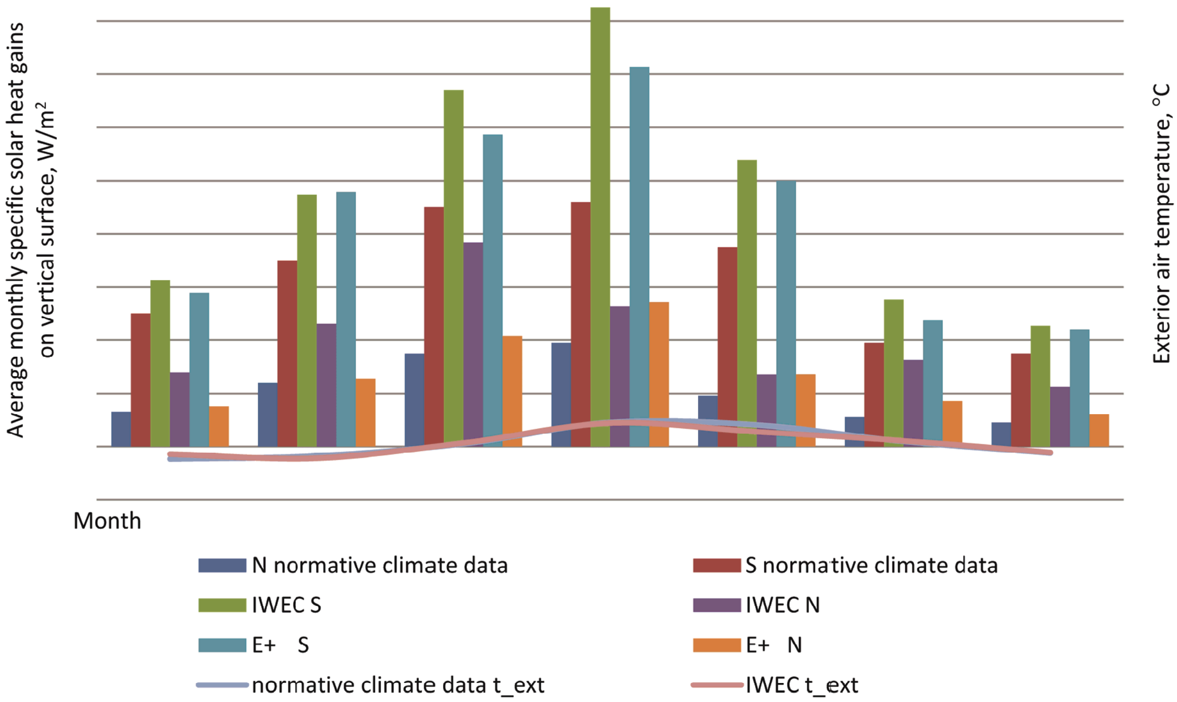

FIGURE 1. *Average monthly external air temperature and solar heat gains*

The external temperature profiles from IWEC weather file and the normative standards almost coincide. Solar heat gains are almost twice as distinguished on the northern surface and 1.5 times on the southern surface as compared with the climatic values from national calculation method of DSTU B A.2.2-12: 2015 [6]. On the northern surface, the difference is up to 5-15 W/m^2 depending on the month. E+ uses IWEC file for a particular city in calculations. The difference between regulatory documents climatic data in Ukraine and IWEC file can make a difference in results of calculating buildings energy efficiency indicators.

Current approaches applied in Ukraine for energy need for heating determination use climatic data from building climatology standard [6, 18]. The use of IWEC file in other approaches, other than the E+ software, has difficulties with information presentation format. To calculate solar heat gains on vertical surfaces, the sun position to the horizon during the year and change during the day has to be determined; the hourly values of solar heat gain per unit of surface for each orientation of building surfaces are averaged monthly. E+ uses several methods for calculating solar heat gains on vertical surfaces. In the created model on E+ base the detailed method of calculation "Full interior and exterior with reflection" is used.

With the use of dynamic models based on the simplified hourly calculation method 5R1C, a classical technique for converting solar heat gains to vertical surfaces of different orientations can be applied [19]. In this technique it is assumed that the diffuse component of solar radiation equally falls on all surfaces and it does not take into account reflected solar radiation from the ground surface. Therefore, while using a simplified hourly method, this feature of converting IWEC file data can make the difference between the results of energy consumption for heating purpose.

The space energy need for heating was calculated according to the IWEC and normative climatic data and included transmission heat losses, ventilation heat losses and solar heat gains to the zone (in all methods for determining energy need, solar heat gains to the space was determined using the same technique proposed in E+). Two extreme cases of determining the energy need for heating are considered: for southern (S) and northern (N) orientation.

Calculation models using aggregate indicators (KTM-204) [4], detailed annual calculation using DSTU N B A.2.2.5: 2007 (HDD method) [2] and monthly calculation method according to DSTU B.A.2.2-12: 2015 [6] are implemented in the Microsoft Excel, the model based on EN 13790 and EN 13786 [11, 12] is implemented on the basis of Mathcad. E+ is a software product for calculating building energy performance without its own graphic interface. E+ uses the Google Sketch-up graphic editor that is synchronized through OpenStudio Plug-in.

The calculation of annual energy need (KTM-204, method GD), monthly energy need (according to DSTU B.A.2.2-12: 2015) and hourly energy need for heating (E+ and 5R1C) is carried out. In the context of the annual energy consumption calculated values using different methods are shown in Figure 2. Considered calculation methods take into account solar heat gains to the building zone, depending on the orientation, except for KTM-204 which considers the average value of solar heat gains during the heating period.

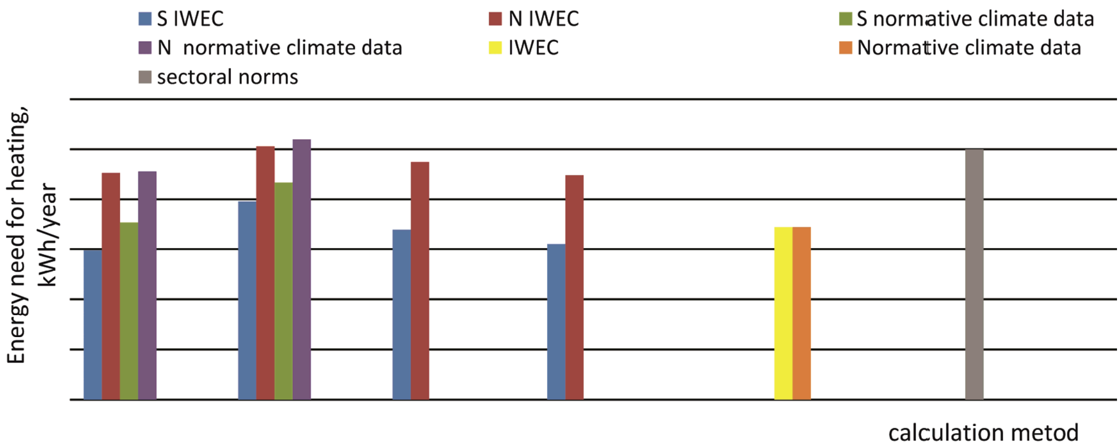

FIGURE 2. *Annual energy need for heating calculated by different methods and weather data bases*

Figure 3 not only shows a comparison of different methods for calculating the annual heating energy need using the same input climatic parameters (IWEC data by the recalculation method given in E+), but also differences in the case of using normative climatic data. Calculation for KTM-204 takes into account solar heat gains in the specific characteristics of heating level. These characteristics are selected based on indicators such as volume, building purpose and construction year, and do not take into account the object geographic location, which leads to overestimating the calculated energy need for the southern regions and underestimating for the northern regions.

Energy need for heating calculated based on E+ is chosen as a reference value for calculating differences in the results of calculations according to given approaches. The difference in energy heed for heating values is higher for southern oriented zone than for northern oriented zone. KTM-204 uses in calculations building energy characteristics that take into account average value of solar heat gains for southern and northern orientations.

Quasi-stationary method of calculation (monthly calculation method according to DSTU B.A.2.2-12: 2015) has the largest differences compared with E+ results. The calculated heating energy need for southern orientation according to the aggregate indicators (KTM-204) gives a difference of about 3%, the detailed method of the HDD has the lowest difference which is about 2%, while difference in calculation according to DBN B.A.2.2-12: 2015 is 12% for northern and 25% for southern orientation. The dynamic methods E+ and 5R1C give almost the same value of energy need for heating difference up to 7% for all orientations.

Unlike the E+ model, the 5R1C model is quickly adaptive to the new geometric and thermal characteristics of the zone. This method does not have its own software platform; it contains only methodological approaches, so the practicality of using this approach depends on the platforms where the 5R1C model is implemented.

Figure 3 shows the heating energy consumption diagram depending on the heating period month.

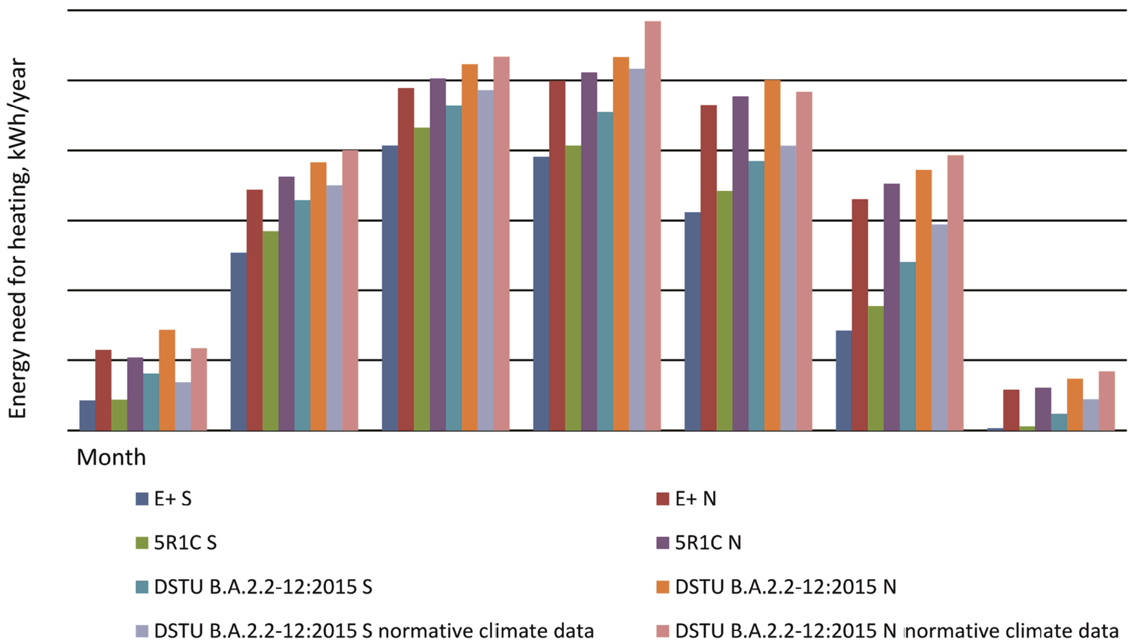

FIGURE 3. *Diagram for heating energy consumption depending on the heating period month*

In general, the lowest values of the monthly energy need for heating are for results based on E+, rather close values are obtained on the basis of 5R1C model; the average monthly difference of received calculations is 40 kWh for S and N. The average monthly difference in the calculation using DSTU B.A.2.2-12-12: 2015 according to IWEC with the results obtained on the basis of 5R1C model is 80 kWh for S and 45 kWh for N. According to the results based on normative climatic data the difference is greater: 135 kWh for S and 65 kWh for N. The national method of calculation has the highest values of heating energy demand using IWEC climatic data, compared with other considered methods, and when using normative climatic values, these values are increasing.

Tendencies in the behavior of heating energy need graphs for hourly dynamic modeling using E+ and 5R1C are almost the same. Figure 4 shows the non-stationary hourly calculation of the heating energy need for a zone oriented to the South using the average daily and average monthly values of exterior air temperature and solar heat gains by 5R1C model and the results obtained on the basis of the national calculation method of DSTU B.A.2.2-12: 2015.

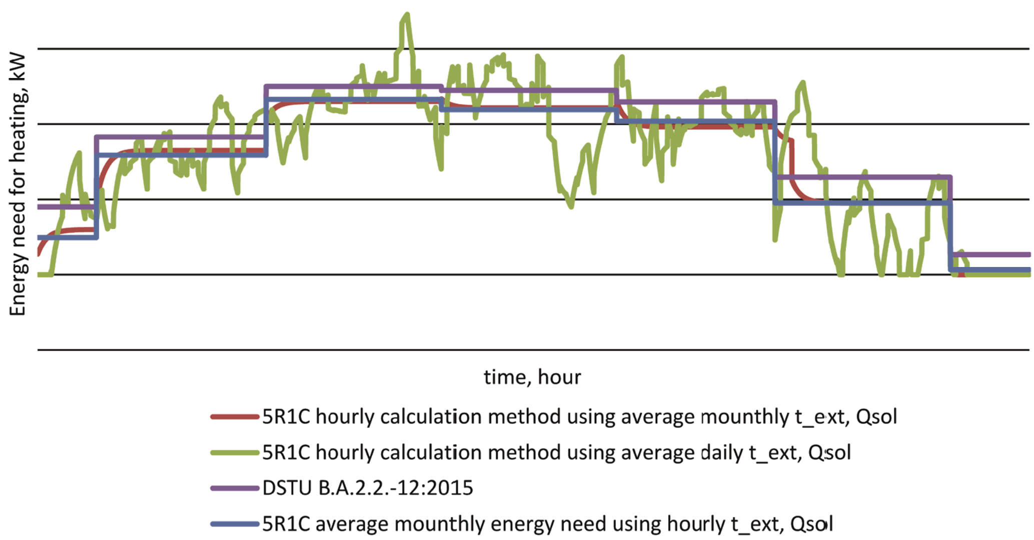

FIGURE 4. *Hourly change of heating level during the heating period for the zone oriented to the South*

Built on the basis of the hourly calculation of heating level change for the average daily and average monthly values of t_{ext} and Q_{sol}, the annual heating energy need using 5R1C model is almost unchanged. The results of hourly energy need for heating using monthly values of weather conditions by 5R1C model have a smooth transition between months, which is due to the heat-inertial features of the model, in contrast to the method of DSTU B.A.2.2-12: 2015. The average monthly energy consumption based on hourly calculation of heating load is almost the same as the hourly calculation results for average daily and average monthly values, but the latter does not allow analyzing the possibility of regulating the heating system in real time.

Hourly changes in the heating level are significant and lead to the fact that in the heating system adjusting mode there are some hours of operation when it is necessary to switch off the heating. This is typical for off-season period, as well as for the anomalous climatic data values for February (the lowest temperatures and the highest values of solar radiation for winter months). Thus, hourly changes in external weather conditions should be used for dynamic regulation.

On the basis of the above methods of energy need for heating calculation, specific indicators of building energy performance are established and compared with the normative values (Table 1). This building refers to the old building stock. Current normative values are used for buildings energy certification, so Table 1 also shows current normative values.

TABLE 1. *Indicators of the specific energy need for heating obtained by different calculation methods (average for southern and northern orientation)*

KTM-204	DSTU N B A. 2.2.5: 2007	DSTU B.A. 2.2-12: 2015	5R1C	E+	The norms of the 2000's	The norms of the 70's
kWh/m³						
40	35	42	38	36	31	47

The specific value of energy consumption in the whole building will be somewhat greater than the values given in Table 1, as the calculation was made for the space having one external wall. Heat losses through the roof and floor will also bring a slight increase in specific indicators. For old buildings, the norms of energy consumption for heating are higher compared to the current standards, due to the increased requirements for the thermal characteristics of building envelope during the construction/design phase. Specific energy consumption indicators for non-stationary calculation methods are lower compared to stationary approaches, with the exception of the HDD method.

Conclusions. Unlike experimental methods of the analysis, the calculation methods allow not only to evaluate a number of influential factors in a complex, but also to evaluate their influence on the value of energy need for heating separately. In the paper, five methods of calculation are compared starting from the aggregated annual indicators and ending up with detailed hourly calculation methods. Stationary methods of calculation significantly overestimate the annual energy need for heating and do not allow the analysis in the daily context. The calculation based on the national method has the greatest difference with non-stationary calculation methods. The two non-stationary methods used to calculate building energy performance give similar results. The model based on 5R1C model is easily adaptable to new input parameters (geometric sizes, thermal characteristics of enclosures, climatic data) unlike the E+ software product. Dynamic calculation methods allow conducting hourly, daily analysis of energy consumption for heating and can be used in predicting the heating level and/or for intermittent heating mode. The difference in the climatic data of the typical year according to the IWEC file from the climatic values in the normative documents in Ukraine also can lead to divergence in calculation results.

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