Numerical Modeling of Energy Consumption in Residential Buildings

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Abstract. Various software for building energy modeling are considered, which allow to determine the amount of energy required for building operation already at the design stage. The uncertainty of energy models for non-residential buildings ranges from ±10 to ±40% compared to the actual energy consumption. Energy consumption of heating, ventilation and hot water supply systems of two multi-story residential buildings was calculated using IES VE modeling software. Actual values of energy consumption in buildings were obtained according to the data of commercial metering devices. The following errors were observed in the energy consumption models of residential buildings in IES VE software compared to the actual building conditions: for heating — up to ±33%, for hot water supply — from plus 38% to plus 95%. The calculation results can be used to estimate the relative energy performance and compare different modeling alternatives, as well as the effectiveness of energy-saving measures, though, cannot be used to estimate the actual energy consumption.

1. Introduction

Building energy modeling (BEM) allows to determine how much energy will be needed by the building during operation already at the design stage [1-14]. Two types of modeling software are used — based on stationary and dynamic (non-stationary) models [1-6]. Dynamic energy modeling software factor in the following:

- geographical location and orientation of the object;
- local weather specifics;
- complex 3d geometry of the object, shading by other buildings and self-shading;
- delayed response of the enclosing structures;
- type and parameters of utility systems (heating, ventilation and air conditioning) installed in the building;
- operation of utility system automation during weather changes;
- operation schedule of the building and utility systems taking into account non-constant operation during the day, week, month, year;
- non-linear connection of utility system elements of the building.

Building energy modeling allows to calculate annual energy consumption savings from various energy-saving measures.

A general overview of the software used for energy modeling is given in [8, 11]. The most feature-rich software includes eQUEST (The Quick Energy Simulation Tool), EnergyPlus, ESP-r (Energy
Simulation Software tool), IDA ICE (Indoor Climate Energy), IES-VE (Integrated Environmental Solutions - Virtual Environment) and TRNSYS (Transient System Simulation Tool) [8]. While these are the most feature-rich software tools, they are also the most complex.

The calculation results obtained from two energy modeling software (eQUEST and EnergyPlus) for an office building were compared to real values of annual gas consumption, which showed very significant differences [13]. The difference between the measured annual gas consumption and the value calculated in eQUEST software is plus 12.51% for February and minus 17.36% for July (the largest recorded difference). EnergyPlus software results differ by plus 62.29% and plus 96.5% (the largest recorded difference).

The estimated uncertainty of building energy models is ±10 to ±40% when they are used to predict the actual performance of non-residential buildings.

Given the complexity of model definition for a building and utility systems, doubts arise that the design decisions based on such modeling are optimal and whether such models can be used to estimate the actual energy consumption of buildings. This study intends to analyze the results of energy modeling of multi-apartment residential buildings using IES VE software in comparison with the actual energy consumption for heating, ventilation and hot water supply.

2. Methods
IES VE software was used to simulate energy consumption of buildings. Building operation was simulated as close as possible to real conditions.

IES VE software includes several modules:
- A module allowing to calculate shading provided by surrounding objects and self-shadowing of the modeled object. This module calculates loads from solar radiation depending month, time of day, geographic location of the object, its orientation.
- A module allowing to set thermal properties of the modeled object, calculate energy loads and model energy flows explicitly. This module allows to obtain information about the operation of the modeled object at any time, taking into account all affecting factors and operation of all utility systems.
- A module allowing to create models of heating, ventilation and air conditioning systems using a detailed description of all equipment and automation. Higher efficiency can be achieved by changing system settings. Operation of each system is modeled during the target year.
- A module that takes into account the air flow between rooms, as well as allows to calculate natural ventilation.

All these modules allow to simulate the studied object operation during the target year. The software allows to study changes of a specific parameter that affects the object, both individually, and in combination with others. Weather files are used for modeling, i.e., files containing the hourly meteorological data for a typical year for a given location. The weather file is as close to real conditions as possible, as energy consumption must be represented with high accuracy.

The actual energy consumption of residential buildings for heating, ventilation and hot water supply is estimated according to the readings of heat and heat carrier meters installed at inlets of central heating network pipelines entering the building.

3. Results
Energy consumption was estimated for two buildings.

The first object is a five-story prefabricated residential building built in 1967 in Kolpino (Figure 1). The building has six sections, 10 one-room, 88 two-room, 18 three-room, 2 four-room apartments, and a total of 118 apartments, which accommodate 308 persons.
Figure 1. Considered residential building (first object) and its model in IES VE.

Data on the energy consumption for heating, ventilation and hot water supply are shown in Figure 2 for three years of observations and based on the results of IES VE modeling. The data are not divided by energy consumption type (only total values).

Figure 2. Energy consumption of a residential building (first object) for heating and hot water supply by months of the year. 1 — first year; 2 — second year; 3 — third year; 4 — calculated using IES VE.
The second object is a twelve-story apartment building located in St. Petersburg and built in 1981 (Figure 3).

For modeling, the existing enclosing structures were defined (heat transfer coefficients of the enclosing structures correspond to the standard design data for I ЛГ-504Д series residential buildings); design external temperature for heating design — \( t_{\text{ext}} = -25 \) °C; average design temperature of internal air for heating design — \( t_i = 18 \) °C.

The design heat flow of the building heating system is \( Q_h = 2,504,142 \) MW.

The results of energy measurements using metering devices and energy consumption calculation for heating in IES VE software are shown in Figure 4.

Building energy consumption calculation was based on the design heat flow of the heating system and the actual average monthly external temperatures (stationary energy consumption model of the building shown in Figure 4). Heat flow of the heating system also factors in the heat flow for heating the infiltrated external air (for ventilation).

The energy consumed per month for heating and ventilation is determined according to the dependence

\[
Q = Q_h \cdot \frac{t_i - t_{mav}}{t_i - t_{\text{ext}}} \cdot z \cdot n, \text{ MWh},
\]

where \( Q_h \) is the design heat flow of the building heating system, MW;
- \( t_i \) is the average design internal air temperature for heating design, °C;
- \( t_{mav} \) is the average monthly external temperature, °C;
- \( t_{\text{ext}} \) is the design external temperature for heating design, °C;
- \( z \) is heating system operation time during a day, h;
- \( n \) the heating system operation time during a month, days.

Figure 3. Considered residential building (second object) and its model in IES VE.
IES VE software allows to assign specific loads and operation schedules of energy-consuming systems for each room. For convenience, the software allows to define the operating conditions of various types of premises using templates. Building structures, ventilation mode, lighting, solar radiation, and other parameters can be defined as well. The schedule (profile) of premise operation defines energy consumption of the premise. The operation schedule for building premises was defined in IES VE when calculating energy consumption for heating.

4. Discussion

4.1. First object
The actual total energy consumption of the building for heating, ventilation and hot water supply significantly differs from the values calculated in the software. The difference reaches plus 47% for winter months. The difference ranges from plus 38% to plus 95% for summer months (June–August). Only hot water supply systems are active during this period. The greatest deviation is observed during the periods of shutdown (May) and activation (September) of heating systems — up to plus 184%.

Steady excessive energy consumption is observed in the actual data relative to the values calculated in the software.

4.2. Second object
The actual energy consumption of the building for heating differs from the calculated values in the range from minus 33% (December) to plus 32% (April). In this case, the accuracy of definition of the weather conditions affects the deviation magnitude.

It should be noted that the building energy consumption modeling results based on the design heat flow of the heating system and the actual average monthly outdoor temperatures (stationary model) have deviations from the actual energy consumption in the range from minus 20% (October) to plus 19% (March). To sum up, this calculation method allows to fairly accurately estimate the energy consumption of buildings for heating. While the calculated energy consumption corresponds to the actual values in contrast to the modeled consumption.
The simulation results significantly depend on the correctness of the operation schedule for building premises (Figure 5), which determines the amount of "domestic" heat loss (regular heat flow coming from electrical appliances, lighting, production equipment, pipelines, people and other sources). Each building has an individual operation schedule.

![Figure 5. Energy consumption in a residential building (second object) for heating by months of the year. 1 — actual; 2 — calculated in IES VE software with specific domestic heat loss per 1 m$^2$ of living space of 21 W/m$^2$; 3 — calculated in IES VE software with specific domestic heat loss per 1 m$^2$ of living space of 10 W/m$^2$; 4 — calculated in IES VE software with a time table of operation conditions defined for each room.]

The time-consuming operation schedule setup for building premises can be replaced by defining the specific domestic heat loss per 1 m$^2$ of the living space. Figure 5 shows energy modelling data with the following values of specific domestic heat loss: 21 W/m$^2$; 10 W/m$^2$.

With a specific domestic heat loss of 9 W/m$^2$ per 1 m$^2$ of living space, the calculation results coincide with the data obtained with the case where the operation schedule was defined for building premises.

5. Conclusions

When IES VE energy consumption models of residential buildings are used to predict the actual building properties, the following uncertainty is observed for heating — up to ±33% and for hot water supply — from plus 38 to plus 95%.

Sources of errors in energy model forecasts usually include unknown and uncertain conditions, such as actual weather, difference between the actual thermal performance of building walls from the design values, oversimplified modeling assumptions, etc. Nevertheless, the calculation results can be used for assessing the relative energy properties and comparing various solutions for utility systems.

The calculation of energy consumption in a residential building based on the heating system design thermal load and average monthly external temperatures has an error of ±20%.
6. References

[1] Bianco V, De Rosa M, Scarpa F, Tagliafico L. A 2016 Analysis of energy demand in residential buildings for different climates by means of dynamic simulation *International Journal of Ambient Energy* 37(2) pp 108-120 DOI: 10.1080 / 01430750.2014.907207

[2] Bubnov Y, Denisikhina D 2016 Energomodelirovanie zdaniy - investing in the past and the future *High technology buildings* Vol 1 1 pp 20–25 URL: http://zvt.abok.ru/upload/pdf_articles/309.pdf

[3] Gerasimov N A 2014 Modeling of energy consumption of buildings - the cornerstone of green design for engineers *Energoberezenie* 4 pp 28-33

[4] Hensen J L M 2010) Building performance simulation for sustainable energy use in buildings *REHVA Journal* vol 47 4 pp 26-30

[5] Hensen J, Werkerk-Evers J, Khairullina A 2014 Mathematical modeling of energy consumption in buildings Development prospects *High technology buildings* pp 58–65 URL: http://zvt.abok.ru/upload/pdf_articles/141.pdf

[6] Volkov A A, Sedov A V, Chelyshkov P D 2014 Energy modeling of construction objects Moscow state builds. un-t. (Moscow: MGSU) 120 p

[7] Denisikhina D, Samoletov M, Khramov A 2017 The new building of the air terminal in Simferopol The practice of modern design *High technology buildings* 2 pp 26–32 URL: http://zvt.abok.ru/upload/pdf_articles/404.pdf

[8] De Rosa M, Bianco V, Scarpa F, Tagliafico L A 2016 Modeling of energy consumption in buildings: an assessment of static and dynamic models *Russian Journal of Construction, Science and Technology* Vol 2 1 pp 12-24 DOI 10.15826 / rjcst.2016.1.002

[9] Reeves T, Olbina S, Issa Raja R A Guidelines for Using Building Information Modeling for Energy Analysis of Buildings *Journals Buildings* Vol 5 Issue 4 pp 1361-1388 doi: 10.3390 / buildings5041361

[10] Song J, Xuelin Z, Meng X 2015 Simulation and Analysis of a University Library Energy Consumption based on EQUEST *Procedia Engineering* Vol 121 pp 1382-1388 https://www.sciencedirect.com/science/article/pii/S1877705815028568

[11] Sousa J 2012 Energy Simulation Software for Buildings: Review and comparison Proceedings of the First International Workshop on Information Technology for Energy Applications, Lisbon, Portugal URL: http://ceur-ws.org/Vol-923/paper08.pdf

[12] Van der Veken J, Saelens D, Verbeeck G, Hens H 2004 Comparison of steady-state and dynamic building energy simulation programs The international Buildings IX ASHREA conference on the performance of exterior envelopes of whole buildings Date: 2004/12/05 2004/12/10 (Location: Clearwater Beach, Florida) URL: https://core.ac.uk/download/pdf/34408977.pdf

[13] Zerroug A, Dzelzitis E 2015 Analysys of results of energy consumption simulation with eQUEST and EnergyPlus 5th *International Scientific Conference Proceedings* Vol 5 Jelgava, Latvia University of Agriculture pp 102-107 URL: http://llufb.llu.lv/conference/Civil_engineering/2015/Latvia_CivilEngineering2015Vol5-102-107.pdf

[14] Zerroug A, Dzelzitis E 2019 Analysis of different building exterior walls insulations using eQUEST E3S Web of Conferences 111 06032 CLIMA 2019 https://doi.org/10.1051/e3sconf/2019111060 9) 201 E3S 111 CLIMA 9 6032 32