Calculation of the Payback Period for Energy-Efficient Building Envelope

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Abstract. The purpose of this paper is to compare energy consumption of residential house with typical wooden frame structure and energy-efficient double framing structure of the external wall and to calculate difference of construction cost with application of both technologies. Research method is based on simulation process in eQUEST software that provides detailed reports on all aspects of building energy-efficiency and allows to determine amount of consumed energy. With help of simulation results produced by eQUEST it is possible to calculate payback period for energy-efficient building envelope based on market prices of construction process.

1. Introduction
In cold climatic zones energy consumption mainly accounts for heating. Despite the fact that Russia has climatic zones from Subtropical to Arctic, biggest part of the country area is located in the Subarctic zone. (Figure 1) Therefore, energy-efficient solutions of the external envelopes of the residential buildings is a key branch of passive technologies and require a deep analysis and a rational approach in the design process of such solutions.

Undoubtedly, energy-efficient solutions lead to a reasonable rise of construction costs. This is a key factor for many potential homeowners, which is able to influence the choice of structure solutions of the exterior wall of the building. The purpose of this article is to compare the construction cost of standard and energy efficient individual residential buildings in a given climatic zone, as well as to calculate the energy consumption for two buildings based on the simulation performed in the eQUEST. Comparison of the additional investments cost in energy-efficient solution of external structures and the difference in the cost of energy consumption will determine the payback period of design solutions. Insignificant payback period of additional investments related to the lifecycle of the building can serve as a good example to demonstrate the feasibility of using more expensive solutions during construction stage. Further operation of the building with an effective passive solution of the outer shell can significantly reduce energy consumption, which is certainly a vital factor for sustainable environmental development in the modern world.
2. Background
One of the leaders in energy-efficient solutions and ecological approach in design field is Canada. Many years of experience in the designing, implementation and operation of wooden frame houses built by so-called "Canadian technology" is worldwide known example of such approach. The climate of Russia and Canada is largely similar, as determined by the same geographical latitudes. (Figure 2) Russian city of Vladivostok was chosen for the calculations, because its climatic conditions are familiar to the author of this paper, and Canadian Montreal was chosen as the location for the subsequent simulation in eQUEST, because the free database of this program includes only North American cities, and the climatic conditions of Montreal are as close to the conditions of Vladivostok as possible.

2.1. Climatic zone
Vladivostok, Russia is located at the junction of several climatic zones (Figure 1). Generally, the climate is defined as "Warm-summer humid continental". Summers are warm but often sweltering with average high temperatures around 26 °C and average low temperatures around 16 °C. Winters are...
usually cold, snowy, windy with an average temperature around -10 °C. However, some winter days come with lower temperatures — below -20 °C. Spring and autumn are pleasantly mild in weather, but prone to sudden temperature changes. Heat season, as well as "Indian summer", comes later due to the proximity of the Pacific Ocean. Sometimes there are snowstorms in November, March and even April.

2.2. Residential House

As an object for the calculations was chosen a typical project of an individual house "Plusvilla 100" (Figure 3) with a wooden frame by "Canadian technology". The project was designed by Plusarkkitehdit Studio for Honkatalot company. The one-storey building with a total area of 96 m² includes a common lounge area, master bedroom, two additional bedrooms, laundry and utility rooms.

The construction of energy-efficient eco-friendly houses with a wooden frame is gaining popularity in Vladivostok now, therefore the evidential base of the effectiveness of certain design solutions with the justification of financial benefits in the long term is strongly required.

2.3. Wood-frame construction

Wood-frame construction has been the option chosen for millions of houses in North America and provides some of the world’s most affordable and comfortable housing. From the days when early Canadian settlers used abundant forest resources for housing materials, wood-frame construction has since become a sophisticated technology supported by a wealth of research and is capable of meeting or exceeding all building science challenges.

2.3.1. Typical wall framing construction. Wall framing includes studs, wall plates and lintels that resist lateral loads and vertical loads from the upper floors, ceiling and roof (Figure 4). Exterior wall studs are the vertical members to which the wall sheathing and cladding are attached. They are supported on a bottom plate and support top plates. Studs usually consist of 38 × 89 mm (2 × 4 in. nominal) lumber and are commonly spaced 400 mm (16 in.) on center. Insulation is usually installed in the stud spaces. Wider 38 × 140 mm (2 × 6 in. nominal) or 38 × 184 (2 × 8 in.) studs can also be used to provide space for more insulation (Figure 4). If the stud space is not deep enough to contain the required level of insulation, wider studs, double walls, or rigid insulation outside the stud space may be used.

2.3.2. Double-frame highly insulated walls. Consider building exterior walls with higher insulation levels than those required by the building code to reduce heating and cooling energy consumption and improve comfort. Double-frame walls have been used successfully in cold climates and where the owners want highly energy-efficient construction. Rigid insulation applied over the exterior of the wall framing will increase the thermal resistance of the walls and reduce thermal bridging caused by the framing (Figure 5). Thermal bridging occurs when thermally conductive materials such as wood
framing conduct heat through the building envelope, thereby bypassing the insulation in the framing cavity, and can considerably reduce the thermal resistance of a wall assembly.

![Figure 4](image4.png) Typical wall detail.  
![Figure 5](image5.png) Double-wall framing detail.

3. Methodology
Research method of this paper is based on simulation of building energy efficiency and energy consumption with help of eQUEST software. Preparation to simulation process starts with building a model of a chosen house and specifying list of parameters that can be critical in the energy consumption field. After completion of simulation process eQUEST provides comprehensive reports that show detailed energy consumption prediction for the chosen interval.

3.1. Simulation software introduction
eQUEST is a sophisticated, easy to use and freeware building energy use analysis tool that provides professional-level results with an affordable level of effort. eQUEST was designed to allow to perform detailed comparative analysis of building designs and technologies by applying sophisticated building energy use simulation techniques but without requiring extensive experience in the "art" of building performance modelling. This is accomplished by combining schematic and design development building creation wizards, an energy efficiency measure (EEM) wizard and a graphical results display module with a complete up-to-date DOE-2 (version 2.2) building energy use simulation program. To get a more complete summary of the features and capabilities of this excellent program users can read the eQUEST Overview.

3.2. Sequence of work in eQUEST
eQUEST allows to construct either schematic building envelop or full comprehensive complex model within the program. There are three input wizards in eQUEST that all have different levels of complexity: Schematic Design Wizard (simple inputs), Design Development Wizard (detailed input) and Energy Efficiency Wizard. Each wizard has extensive default inputs that are based on California Title 24 building energy code. One more option is detailed DOE-2 interface, that can be used in special cases if highest level of detailing is needed. Long-term average weather data (TMY, TMY2, TMY3, etc.) for more than one thousand North American locations are available via automatic download within eQUEST.

The eQUEST Schematic Design Wizard firstly requires general information about building design and then progressively delves deeply into details. Building description process consists of 53 data entering steps - each represented by a wizard screen that provides easy-to-understand choices of components and system options. It also offers advice in the form of "intelligent defaults" for each choice. These defaults are marked with green colour and based on information gathered earlier during
description process. Although the building description process can get quite detailed there is no need to complete every single step in the wizard. There is possibility to skip unnecessary steps if user is already satisfied with detailing level of model. At that point the wizard fills in missing information using eQUEST intelligent default process. In addition, eQUEST automatically skips steps that do not apply to chosen design.

After compiling description, eQUEST produces detailed simulation of created building model, as well as estimation of energy consumption. Although these results are generated quickly, they are quite accurate because eQUEST utilizes the full capabilities of DOE-2 (the latest version of a well-respected and popular building energy simulation program developed by the US DOE).

3.3. Simulation process in eQUEST

3.3.1. Starting point. Process starts from choosing wizard in main window of eQUEST. In our case we have chosen Schematic Design Wizard.

3.3.2. Parameter input. Sequence of following floating windows are used to input all parameters related to the building design: location in climatic zone, geometrical size and orientation of the house, structure of envelope and its material with different options for insulation, openings percentage, HVAC systems and etc. (Figure 6)

**Figure 6. General information and building footprint.**

As mentioned above, the free climate base of eQUEST has information only about North American cities. Therefore, a North American city with climatic conditions as close as possible to Vladivostok was found. To do this we used an interactive map “Find cities with similar climate”, which allows to fulfill clear comparison of the climates of different cities around the world. This map has been created using the Global Environmental Stratification. As it turned out, the climate twin of Russian Vladivostok is Canadian Montreal (Figure 7), which is located in the same climatic zone and has identical average annual temperatures and amount of rainfall.

**Figure 7. Comparison of Vladivostok and Montreal average annual temperature.**

The main compared parameter is energy efficiency of the external envelope of the building with different structural design. Other parameters must be unchanged and strictly fixed for the purity of the
experiment. The purpose of this simulation is to compare amount of consumed energy by house with two structural types of the outer shell. As an initial variant was chosen Standard Wood frame 38 × 140 mm (2 × 6 in.) and as a more energy-efficient alternative - Double Advanced Wood frame. Structural characteristics of the external walls of these two types are described in details in the previous "Wood frame construction" section of this paper.

Despite the higher cost, wooden energy-efficient windows, with triple-glazing and cameras filled with argon, are quite popular and widespread in Vladivostok. Therefore, they were chosen as window for following simulation. Overall model detailing process consists of fifty-three steps detailing each aspect of the building being prepared for the simulation. However, thanks to the intelligent algorithm of eQUEST there is no need to fill in each parameter manually. User only needs to choose the most critical parameters and all the rest will be completed with "intelligent default" process by wizard.

3.3.3. Specification of model. After completing the building description process in the dialog boxes, eQUEST generates a simplified model. Despite the fact that the visual appearance of generated model is quite primitive (for example in comparison with REVIT models), it has an extra broad range of physical parameters as well as a full set of engineering systems that are required for further simulation.

As we are satisfied with all characteristics of generated model we can get calculation of energy consumption by simulating building performance in eQUEST. Simulation can be started using the command Simulating Building Performance to achieve this. After a short-term calculation process, we can get a comprehensive report with all the sophisticated parameters.

3.3.4. Energy Efficiency Improvement. In order to increase energy efficiency and calculate energy consumption using improved structure of the external wall it is necessary to run the Energy Efficiency Measure Wizard command. In opened Energy Efficiency Measure Creation window select the Building Envelope category and in the next scroll from the available options select Exterior Wall Insulation.

![Figure 8. Energy Efficiency Measure Wizard window.](image)

In order to select required for comparison Double Advanced Wood Frame we need to go to EEM Run Details (Figure 8) and to find the desired option from the drop-down scroll that is called Construction. Once the new parameters have been selected, the simulation process can get started again. New reports with comparison of the initial and recalculated energy consumption in the summary chart is available after accomplishment of simulation.

4. Results and discussion

This section is devoted to the analysis of calculations obtained as a result of the simulation. Completed eQUEST simulation allow to consider quantitative information and compare the values for the two types of wooden frames.
Comparison of the consumed amount of electricity and gas demonstrates the effectiveness of double-wall framing. Usage of a more efficient wall structure can reduce electricity consumption by 330 kW and 10'905'000 BTU (4% and 12% respectively) per year, which is a substantial benefit in monetary terms. A significant difference in the percentage of energy savings and gas savings occurs because of the fact that external wall design has most serious impact on savings of the heat that is provided by the gas, while a small percentage of electricity is used for cooling of air only during several summer months.

4.1. Monthly Energy Consumption

![Figure 9](image1.png)

Figure 9. Monthly energy consumption of house with typical wood frame.

Electricity consumption peak of house with typical wood frame in July: 1'040 KWh. Gas consumption peak of house with typical wood frame in January: 15'300'000 Btu. Main uses of house with typical wood frame: miscellaneous equipment, space cooling, space heating, water heating. Minimal use for ventilation fans, refrigeration and heat rejection.

![Figure 10](image2.png)

Figure 10. Monthly energy consumption of house with double-wall framing.

Electricity consumption peak of house with double-wall framing in July: 950 KWh. Gas consumption peak of house with double-wall framing in January: 13'600'000 Btu.
4.2. Annual Energy Consumption
Electricity annual consumption of house with typical wood frame: 8’380 kWh, gas annual consumption of house with typical wood frame: 98’480’000 BTU.
Electricity annual consumption of house with double-wall framing: 8’050 kWh, gas annual consumption of house with double-wall framing: 87’575’000 BTU.

4.3. Comparison of Monthly Energy Consumption.

![Figure 11. Comparison of Monthly Energy Consumption.](image)

4.4. Calculation of the additional investments payback period.
In order to calculate the payback period of additional investments in energy-efficient structure of the external walls, it is necessary to calculate the cost of building construction with usage of two types of structures, as well as the amount of saved finances from electricity and heating in case of implementation of the second option [1-10].
The market value of capital construction of a wooden house without interior finishing with the use of a standard wooden frame is 17’870.0 rubles per square meter of the total area in 2018 in Russia. The cost of construction of a residential house with the use of double-wall framing is 18’760.0 rubles. Accordingly, the cost of construction of a residential Plusvilla house with an area of 96 m2 will be:
- Plusvilla house with typical wood frame – 1’715’520.0 Russian rubles
- Plusvilla house with double-wall framing – 1’800’960.0 Russian rubles

In order to calculate the cost of the house operation we need to know the established rate for one kilowatt per hour of electricity, as well as the cost of one British Thermal Unit produced by gas. To simplify the calculations, we took the standard electricity tariff in Russia, and also we transferred BTU to kWh. One kilowatt per hour (kWh) is equal to 3’412.128 British Thermal Units (BTU).
Plusvilla house with typical wood frame consumes annually 98’480’000 BTU that equals 28’862 kWh. The annual electricity consumption of that house is 8’380 kWh. Therefore, total annual energy consumption is 37’242 kWh.
Plusvilla house with double-wall framing consumes annually 87,575,000 BTU that equals 25,666 kWh. The annual electricity consumption of that house is 8,050 kWh. Therefore, total annual energy consumption is 33,716 kWh.

The electricity cost in Russia is 3.54 rubles for one kilowatt per hour since January 2018, respectively, the cost of house operation for one year is:

- 131,840.0 rubles for Plusvilla house with typical wood frame
- 119,350.0 rubles for Plusvilla house with double-wall framing

The difference of the house building cost with an energy-efficient structure of the external walls is 85,440.0 rubles, while the energy saving is 12,490.0 rubles per year. Therefore, the payback period of the energy-efficient structure is 6.8 years. That is quite a short period in comparison with a lifecycle of building, which is about one hundred years.

5. Conclusion
The aim of this work is to demonstrate how eco-friendly approach to design can affect the choice of structure, which in turn can lead to significant energy savings and also savings of finance. Despite the fact that the use of double frame structure of the external wall seems for most people to be an unnecessary waste of money (which confirms the widespread use of a standard wooden frame house), in the medium term it is a profitable investment and a rational solution.

The result of the simulation shows that usage of energy-efficient structure of the external wall can reduce energy consumption by 4%, and gas by 12%. With usage of energy-efficient roof and foundation structures these percentages can increase significantly. Improved modern thermal insulation will also give a significant increase to the overall efficiency of the building envelope. A positive effect on energy saving can be achieved by the selection of energy-efficient equipment for heating and ventilation. With application of any combination of the abovementioned additional investments the expenses would not be ineffective. Any investment in solutions of ecological character (whether active or passive) will be paid back, only payback period can slightly increase. On the example of a particular Plusvilla house with area of 96 m², we proved that double-wall frame structure with a slight overpayment during construction period pays off in less than seven years and allows to save 12,490.0 rubles annually on the operation of the house.

In conclusion, it is important to remind that the relevance of usage of energy-efficient and environmental friendly structures is not only conditioned by financial savings and personal benefits, but also by the responsibility towards society and future generations of our planet. Reducing the consumption of any resources is a highest priority in all developed countries nowadays. Therefore, proven financial feasibility of seemingly more expensive solutions and the awareness of the wider society is vital for future prosperity of humankind.

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