High energy efficiency retrofits of residential buildings

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Abstract
Building energy efficiency retrofit is considered as a valuable way to improve energy efficiency of high-energy-consumption buildings. The sustainable retrofit helps to integrate sustainable development strategy into existing buildings and retrofit projects.
This paper presents findings of a study on problems and opportunities of retrofitting the old houses built in Ukraine. The research defines and virtually implements an incremental intervention strategy, which incorporates different retrofit packages for a typical house. Consequently, the upgrade packages have been simulated to assess their impact on the house's thermal performance. The paper reports on effective ways of preserving the integrity of such a house, while improving its thermal performance to the EnerPHit standard, and discusses the benefits of introducing this holistic approach into Ukraine's retrofit practice.
Keywords: ENERGY RETROFIT; ENERPHIT; VERY LOW-ENERGY HOUSES; ENERGY BALANCE

1. Introduction

According to the International Energy Agency, buildings are responsible for 32% of the total final energy consumption and around 40% of the primary energy consumption in most of its member countries [1]. The growing awareness of the impact of the built environment on energy security that started with the 1973 oil crisis has made building energy efficiency a common target of many national energy conservation policies.

An increased effort towards consistent inclusion of the existing building stock in policies and programmes for the improvement of energy efficiency is crucial to achieve tangible savings in building-related energy consumption and CO_2 emission reduction. This is particularly relevant, as in many urban transformations retrofitting is often more effective than demolition and reconstruction both economically and environmentally as demonstrated by studies using Life Cycle Analysis [2]. Moreover, preserving the existing buildings influences positively local communities, promoting resilient and sustainable urban living patterns.

According to Csoknyai [3], the refurbishment of panel buildings (i.e., prefabricated multistorey buildings constructed from concrete or reinforced concrete panel) in CEE (Central and Eastern Europe) region is an urgent issue nowadays [4]. Such situation is caused by the fact that although holding structures of panel buildings are expected to endure for 50-100 years, windows and other building service systems are already out of order as their service lives are about 30 years. In Ukraine, not only panel buildings, but also brick constructions built after World War II are currently in extremely poor state and require refurbishment which allows the improvement of their energy performance to be carried out simultaneous.

In 1999, the Programme of Residential Buildings of First Mass Construction Series Reconstruction was approved by Cabinet of Ministers of Ukraine [5]. According to this Programme, the buildings, constructed from panel and brick materials during 1960s-1970s, total as many as 72 million m^2 of living area, i.e. 23% of total Ukrainian residential stock. The Programme implied thermal insulation of external walls and water pipes, installation of energy saving windows and balcony doors, equipping houses with flow meters for water, natural gas, and thermal energy. Such measures were expected to result in 1/3 reduction of energy consumption by residential stock.

Furthermore, the comparison of the Ukrainian building stock aging versus the data from the other European countries is quite interesting. Based on 2008 European Commission Report [6], Table 1 shows the information on the same age categories of the houses as those in Germany, Czech Republic and Lithuania.

As the data shows, the age of the building stock in Ukraine is similar to the building stock in EU countries.

The other issue we propose to consider is the classification of multi-story residential buildings in Kyiv is given in Table 2.

The current needs to reduce the energy consumption by buildings spread worldwide to pursuit the goal of low and very low energy buildings, thus has appeared different definitions and concepts concerning this problem. Despite the differences, all of them have in common the idea that very low energy houses have a design that enables low energy demand due to sufficiently well insulated thermal envelope for buildings to have minimal heat losses, compact shape and no thermal bridges for even minimal heat losses, energy efficient windows facing sun allowing passive solar gains, good airtightness for controlled ventilation and reduction of heat losses and moisture damages [7]. Hence, these buildings have significantly lower energy demand than the buildings just meeting the mandatory buildings regulations, which typical criteria are 25-50% better than minimum requirements [7]. Besides the obvious benefit of low energy consumption, the very low energy house has many benefits in terms of the comfort and the indoor climate.

Table 1. Age groups of buildings in European countries

Built period	Ukraine	Germany	Czech Rep	Lithuania
Before 1919	5%	14 %	11%	6%
Between 1919-1945	13%	14%	14%	23%
Between 1946 –1970	51%	46%	25%	33%
Between 1971-1980	16%	13%	22%	18%
After 1981	15%	13%	28%.	20%

% is defined from the number of buildings

Table 2. Classification of multi-story residential buildings in Kyiv

Name	Series	Construction year	Number of buildings, units	Share, %	Stories
"Pre-revolutionary"	–	before 1917	1556	12.9	1...8
"Stalinky"	–	1920s – mid 1950s	1898	15.7	2...13
Panel buildings	"Khruschevka", "Cheshka", "464"	mid 1950s – late 1980s	1695	14.1	3...12
	"96", "134", "BPS-6"	1970s – 1980s	1041	8.6	9...16
	"T", "KT", "APPS"	1970s – 1980s	861	7.1	9...22
Brick buildings	"Khruschevka", "MM-640", "K14", "1-318-35/36"	mid 1950s – late 1980s	2878	23.9	2...14
	"87", "Departmental houses", "KP"	before 1991	809	6.7	4...20
Modern panel buildings	"APPS lux", "KT Uyut", "B-5", "ES", "Individual project"	after 1991	286	2.4	9...26
Modern brick buildings	"Individual project"	after 1991	1038	8.6	2...28

Numerous voluntary standards for heating energy demand aiming high comfort with minimum consumption have been developed in various countries for residential and non-residential buildings.

One of the examples to illustrate the stated above is Passive House standard, which has been developed in Germany by the Passive House Institute (PHI) and is currently considered the most demanding standard on buildings' energy efficiency [8]. Thus, a passive house's annual heating demand is to be equal or less than 15 $kWh \cdot m^{-2}a^{-1}$ (assuming a uniform indoor temperature of 20 ºC) or, the heating load is to be equal or less than 10 $W \cdot m^{-2}$, the primary energy use - equal or less than 120 $kWh \cdot m^{-2}a^{-1}$, the airtightness level (n_{50}) - equal or less than 0.60 h^{-1} and thermal comfort is to be met for all living areas during winter as well as in summer seasons, with not more than 10 % of the hours in a year over 25°C (to control the overheating). To achieve these requirements it entails a high performance thermal envelope combined with mechanical ventilation with heat recovery to ensure high indoor air quality. Additionally, the building envelope has to comply with several thermal requirements for Central European countries, such as very well-insulated opaque building components and efficient mechanical ventilation with heat recovery. For the most cold climates, this means a maximum value of 0.15 W/(m²K) for the heat transfer coefficient (*U-value)*. Window frames must be well insulated, which means a maximum *U-value* of 0.80 W/(m²K) and *g-values* around 50% for the most cool climates. Finally, uncontrolled heat leakage through gaps must be smaller than 0.6 of the total house volume per hour during a pressure test of 50 Pascal (both pressurized and depressurized) and the absence of thermal bridges should be guaranteed [8].

Passive House standard represents a reduction factor up to 12 for heating load in mild climates (such as Southern Europe) and up to 30 for cold climate regions with minimal insulation requirements. In cases, the buildings are not currently heated up to comfortable temperatures, the adoption of a high performance envelope can aid in achieving comfortable conditions while still reducing heating energy consumption in absolute terms.

For existing buildings, the EnerPHit standard has been developed by limiting the annual heating demand to a maximum of 25 $kWh \cdot m^{-2}a^{-1}$, assuming a uniform indoor temperature of 20ºC. The maximum value of the air tightness level (n_{50}) is considered equal to 1.0 h^{-1} [8]. In Germany, more than 13000 Passive Houses have been built since the 1990s and the energy renovation according to the EnerPHit standard is growing, being considered by some authors as one of the fastest growing energy performance standard in the world.

The objectives of this study are as follows: 1) to evaluate the current thermal performance of a typical residential building with high energy consumption using PHPP calculation tool; 2) to assess the impact of the thermal upgrade of walls, roof, basement ceiling, windows, and different ventilation strategies on space heating energy consumption and heat load.

2. MATERIALS AND METHODS

2.1. Dwelling archetype and construction details

The building under study is a 5-storey residential building of 2343 m², located in Kyiv (Ukraine) and built in 1966 (Fig. 1).

Figure. 1. The 5-storey building built in 1966

The external walls of the building consist of interior plaster and brickwork with their corresponding U-value of 1.24 W/(m²K). The top floor ceiling is composed by a slab and sand-cement mortar and its relative U-value is 2.765 W/m²K. The basement ceiling (adjacent to ventilated basement) is made up of two layers: parquet, concrete slab. The corresponding U-value of it is 1.629 W/(m²K). The windows have double glazing 4/12 mm in timber frames. The U-value of the existing windows is 2.7 W/(m²K). The ventilation type of the building foresees the only window ventilation. The system has showed the air change rate at pressurized test as intensive as n_{50}=5 h^{-1}.

Tables 3 describes the baseline construction details.

2.2. Retrofit measures

In general, the retrofit packages are designed to achieve progressive improvements of the envelope's thermal performance and airtightness up to the EnerPHit standard (heating demand =25 kWh/(m²a) and air permeability rate n_{50}<1.0 h^{-1}). In the case under analysis, in order to perform thermal simulation, a "base case" is defined to stand for the conditions of the house as originally built, without insulation.

Table 3. Base case construction details

Element	Construction	U-value (W/m²K)
External wall	15 mm interior plaster+380 mm brickwork	1.24
Top floor ceiling	220 mm concrete slab +50 mm sand-cement mortar	2.765
Basement ceiling	22 mm parquet+220 mm concrete slab	1.629
Doors	metal	3.704
Glazing	Double glazing 4/12 mm in timber frame	2.7

The two upgrade variants are considered: variant 1 “Moderate thermal insulation” and variant 2 “Passive House with ventilation heat recovery unit”. The proposed intervention strategy comprises a series of coherent, effective, discrete and independent retrofit packages, respectively concerning the improvement of thermal performance and airtightness, as well as the installation of new windows, effective thermal insulation and mechanical heat-recovery ventilation system (in case of “Passive House” with ventilation heat recovery unit”).

Table 4 describes the building fabric improvement measures and the post-retrofit construction U-values. The air change rates at pressurized tests are n_{50}=3.0 h^{-1} (variant 1) and n_{50}=1 h^{-1} (variant 2).

2.3. Thermal Simulation and Calculation with Passive House Planning Package

Based on the above reported materials, the next phase of the study was testing upgrade retrofit packages with the Passive House Planning Package (PHPP), the Excel spreadsheet-based design tool specifically developed by PHI to assist architects and designers in planning and verifying Passive Houses towards certification. It calculates building components' U-values, heating, cooling and primary energy demand, ventilation rates for comfort as well as the risk of overheating in the warmer season. Moreover, it compiles climate data from many locations worldwide, including Kyiv (Ukraine). Validated with dynamic simulation tools as well as with measured data, the PHPP energy balance module has proven to be surprisingly precise.

For this study, the new PHPP 9 was used, which allows the direct comparison of different variants, together with their economic evaluation. Additional retrofit options were also tested to verify the specific impact of airtightness, mechanical ventilation versus natural ventilation and window performance. The aim of this investigation is to assess under what insulation, ventilation and airtightness conditions the EnerPHit requirements could be met.

3. RESULTS, ANALYSIS AND DISCUSSION

This section contains the analysis and discussion of the thermal calculation results of pre- and post-retrofit variants. The parameters for analysis include annual space heating energy consumption per m² as well as comparison of heat flows (losses and gains).

3.1. Base case space heating energy consumption

As a first step, the thermal performance of the original building was studied. The thermal balance was obtained through the calculation of Passive House Planning Package (PHPP9) application. The following preliminary results concerning the energy demands were received through the PHPP9: heating demand of 197.9 $kWh \cdot m^{-2}a^{-1}$ and primary energy demand of 546.5 $kWh \cdot m^{-2}a^{-1}$.

3.2. Impact of retrofit measures on space heating energy consumption

Figure 2 shows specific annual heating demand [kWh/(m²a)] for each of the upgrade scenarios calculated with PHPP9.

The graph illustrates how the improvements have modified the poorly thermally insulated house (base case or existing building) into the house with moderate

Table 4. Retrofit measures, and improved U-values of the building elements

Element	Upgrade variant	Modification to base case construction	Improved U-value (W/m²K)
External wall	1	100 mm polystyrene insulation	0.302
	2	300 mm polystyrene insulation	0.120
Top floor ceiling	1	100 mm blown mineral wool (λ=0.04 W/mK)	0.349
	2	350 mm blown mineral wool (λ=0.04 W/mK)	0.106
Basement ceiling	1	170 mm polystyrene (λ=0.04 W/mK)	0.206
	2	350 mm polystyrene (λ=0.04 W/mK)	0.110
Glazing	1	double thermally insulated glazing 4/16, argon 90 %, in PH frames with good thermal quality	1.28 – 1.29
	2	double thermally insulated glazing 4/16, argon 90 %, in PH frames with good thermal quality	1.28 – 1.29

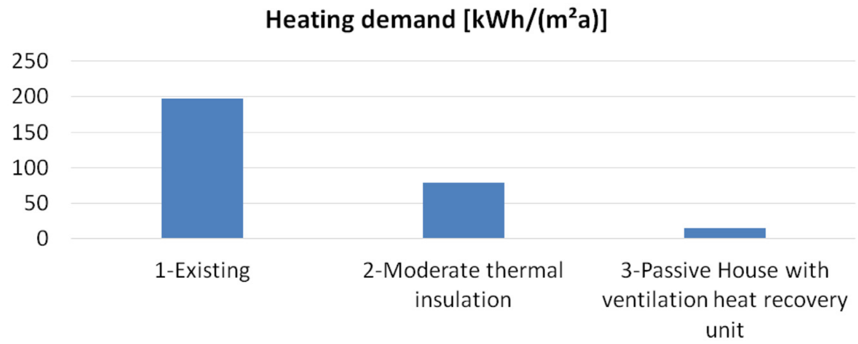

Figure 2. Comparison of specific annual heating demands (kWh/(m^{2}a)) and the base case and different retrofitting packages

thermal insulation, reducing heating demand from 197.9 kWh/m^{2}a to 79.3 kWh/m^{2}a (according to annual method). A more significant result is that, by improving the thermal insulation of ceiling, floor and external walls as well as using ventilation heat recovery unit and increasing air tightness in the path to meet the EnerPHit standard, annual heating demand drops down to 15.2 kWh/m^{2}a .

Summarizing, the results also have proven the positive impact on heating demand reduction of two factors: thermal envelope insulation and air infiltration. This becomes evident through the analysis of outward and inward flows (losses and gains) through the envelope (refer to Table 5 with details of benefits from each intervention).

The comparison between the heat flows of the existing house and those meeting the EnerPHit requirements shows a significant reduction of heating demand due to new windows, improved airtightness (n_{50} drops from 5 h^{-1} to 1 h^{-1}) and thermal envelope insulation.

The comparative analysis of different ventilation systems has shown the effect of MHRV on heat demand. The impact of airtightness and ventilation is evident when comparing the heat flow breakdown of the variants "Existing building" and "Passive House with ventilation heat recovery unit", where the installations of mechanical ventilation heat recovery unit (MHRV) and new efficient windows cause the huge decrease in ventilation losses (from 70.3 kWh/m^{2}a to 5.1 kWh/m^{2}a). In winter, a balanced MHRV proves to be a key to maintaining heating demand below the limit (EnerPHit standard) of 25 kWh/(m^{2}a).

Specific losses and gains for the upgrade "Passive House with ventilation heat recovery unit" are given in Figure 3.

Additionally, achieving the required airtightness levels can be challenging in retrofit interventions, where existing floor, ceiling, internal load bearing walls and partitions are maintained by various techniques, as the additional airtight layers added on top surfaces of existing floor, wall and ceiling are interrupted by the structure of each internal partition, and therefore the sealing is complicated. Airtightness though as well as ventilation heat recovery unit are key issues in reducing heating demand.

3.3. Recommendations for future research

This paper presents ongoing work on the development of an integrated framework for the retrofit of old dwellings. Its object is to encapsulate energy, comfort, cost and value propositions for different stakeholders. The future work shall increase the number of simulated scenarios (e.g. building orientation, a renter or an owner behaviour), use alternative overheating criteria and validate the existing simulation assumptions and outputs against monitored data.

However, with the desired extremely low energy consumption involved, performance could be affected by thermal bridging and airtightness issues.

Table 5. Comparison of heat flows (losses and gains) of the retrofit packages to meet the EnerPHit standard calculated with PHPP9 (monthly method)

Upgraded variants	Transfer heat losses, kWh/(m^{2}a)	Ventilation heat losses, kWh/(m^{2}a)	Total heat losses, kWh/(m^{2}a)	Heat gains (available solar heat gains+ internal heat gains), kWh/(m^{2}a)	Annual heating demand kWh/(m^{2}a)
Existing building	203	70.3	273.3	75.4	197.9
Moderate heat insulation	57.4	63.6	121.1	41.8	79.3
Passive House with ventilation heat recovery unit	36.1	5.1	41.2	26.0	15.2

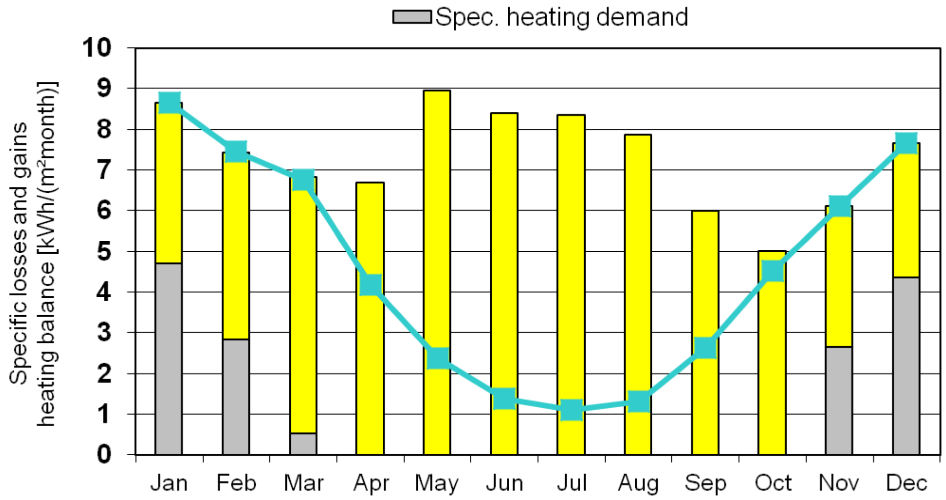

Figure 3. Specific losses and gains for the upgrade "Passive house with compact HP unit" (monthly method)

The further research is required to develop thermal bridge-free construction details and effective solutions for a continuous airtight envelope. Indeed, thermal insulation can easily be installed in existing houses to guarantee the necessary thermal performance of the envelope, but achieving the airtightness levels required by the EnerPHit standard can be challenging, due to construction and preservation issues.

Finally, a complete assessment should be made on the expenses of the upgrades and a cost-benefit analysis of the investments over a long-term period for the Ukrainian national stock upgrade to EnerPHit standard. The complete retrofit intervention in the cost-benefit analysis should include a completely thermally insulated and airtight envelope, high performance windows with external shadings to prevent overheating in summer, and supplemental space heating (normally distributed through the low-volume MHRV system).

Conclusions

This study uses a holistic retrofit approach to develop a retrofitting strategy based on incremental interventions that are defined and evaluated using a case-study - a house located in Kyiv (Ukraine). The use of thermal simulation and PHPP calculation has allowed the assessment of different factors impact –such as wall thermal insulation, ventilation mode, and air infiltration–on the building energy performance.

Moreover, the assessment of a basic retrofit package–only including external walls insulation (variant "Moderate heat insulation") and reducing the infiltration rate to 3 h^{-1} –shows that such interventions are not sufficient for effectively reduce energy consumption and attaining the requirements of EnerPHit standard. Through the comparative evaluation of the results of different retrofit interventions simulated with the PHPP software, the study illustrates how effective results can be achieved with comprehensive retrofit interventions that combine the whole building envelope insulation and airtightness enhancing with controlled ventilation and an effective heat recovery unit.

However, airtightness is the main challenge and the further empirical research is needed to develop technologically and economically viable retrofit details for a thermal bridge-free and airtight envelope.

Finally, it is important to note that housing retrofit is a case-specific, and evolutive, since attaining the complience with high performance-based standards such as EnerPHit benefits from the steady improvement in the construction technology.

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Experimentally determined MSW sample incineration heat and revealing its auto-combustion capability

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Abstract
The current research experimentally simulates the combustion processes for municipal solid wastes of a given composition with a boiler-utilizer pursing the objective to study the opportunities for autocombustion and to determine the heat of incineration. The research is carried with the samples made from municipal solid wastes (hereinafter referred as MSW) simulating their average morphology in the city of Kyiv, Ukraine. Their incineration was performed in the laboratory boiler-utilizer and the incineration heat of 1 kg of solid waste has been defined. The values of incineration heat, as established by the experiments, correspond to the predicted values. However, it was not possible to keep the required temperature of 850 °C in the experimental equipment and to reach auto-combustion even with that MSW composition, with which auto-combustion is possible in accordance to the Tanner diagram. In the article, we substantiate that the MSW combustion process for the industrial furnaces cannot be studied with an experimental boiler-utilizer; for this purpose it is expedient to use the appropriate calculation models based on the thermal balance sheet of the furnace. For the practical use, the research has showed that the industrial plants and sites, which practice MSW incineration, can quite accurately determine the heat of MSW incineration by direct combustion of the appropriate samples.
Keywords: MUNICIPAL SOLID WASTES, TANNER DIAGRAM, HEAT OF INCINERATION, MODEL SAMPLE, BOILER-UTILIZER, PREDICTED VALUE.