ENERGY EFFICIENCY AND ECONOMIC ANALYSIS OF RETROFIT MEASURES FOR SINGLE-FAMILY RESIDENTIAL BUILDINGS

by

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The research elaborates various solutions using detailed economic evaluation and energy efficiency calculation and simulation technology for formulating applicable, energy and cost-efficient retrofit solutions of single-family residential buildings located in temperate climate areas. Primarily the annual energy demand for a reference existing single-family residential building was determined. The economic analysis was performed for six formulated refurbishment scenarios in order to determine which of the scenarios will demonstrate optimal performance both in energy and cost efficiency. A feasibility study was performed for the most efficient scenario, which included an economic evaluation of low temperature radiant heating systems were three energy suppliers (oil, natural gas and electricity for air to water heat pump) were compared. According to financial analyses the optimal scenario includes the replacement of windows, installation of 15 cm expanded polystyrene thermal insulation, low temperature radiant floor heating, with a payback period of ten years.

Key words: *energy performance simulation, economic evaluation, EnergyPlus, energy demands analysis, energy efficient retrofit*

Introduction

Much effort regarding energy savings has been spent due to large environmental problems and limited energy sources. According to the European Energy and Climate Change Policy and its targets for the year 2020, different options and solutions are explored in order to reduce CO_2 emissions. One of the opportunities is the energetic reconstruction of individual houses. The residential sector in Slovenia started a serious refurbishment process by encouraging the population to undertake energy efficient measures with multiple financial opportunities and benefits.

The motivation of the research was to formulate a refurbishment method, which would demonstrate high performance in energy efficiency due to economic benefit.

The scope of the research was to develop a reference model, which is both energy and cost optimal, oriented for a wide audience with a preferable and applicable performance. The aim was to analyse various cases for energy demand reduction and to evaluate the economic benefits for the refurbishment.

Applied research methodology was detailed dynamic building performance simulation technique in order to optimize the energy performance of a typical residential building for the

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climate conditions of Slovenia and to find efficient solutions for the envelope's thermal insulation thickness and adequate heating system. The dynamic simulations were performed according to the ASHRAE 90.1 standards [1] with EnergyPlus software. In [2] ASHRAE climate zones refer to worldwide locations. The European weather data for Slovenia were used from the data packages of ASHRAE Climate Design Conditions [3] and EnergyPlus Weather (EPW) Data by Region [4].

Integrated design process and dynamic energy simulation is widespread in the field of energy performance optimization and strategic planning of building energy efficiency. Dynamic simulation is used in determining construction properties, occupant comfort, HVAC system energy demands, energy conservation techniques *etc*. [5-8]. In one of our previous researches, we used multi-criteria optimization methodology to determine an optimal energy retrofit solution in case of adequate envelope glazing selection [9]. Our previous research demonstrated an optimized building envelope model using multi-criterion optimization methodology in order to determine efficient window to wall ratio and window geometry in the function of indoor visual comfort, followed by the assessment of envelope's influence on the annual energy demand. Optimal design methods for cooling systems considering cooling load analysis using simulation techniques is a topic of interest respectively [10]. Energetic and environmental performance assessment can be parallel analysed [10, 11]. Extensions on the urban level were made, respectively, from the aspect of building envelope design for overall energy efficiency [12]. Residential building refurbishment methods have been analysed in multiple researches for different climate conditions [7, 13, 14]. Authors used two calculation methods for the energy consumption for heating: the quasi-steady-state method and the dynamic simulation method. The values obtained by measuring have proven that the difference in the energy consumption was 2.7% and 4.8% [15]. In the province of Vojvodina, Serbia the building operating costs as well as energy consumption falls on the owner. The authors state that this aspect further deters the user from rational energy use during building operation, however implementation of energy management system would remove even this negative irrational attitude towards energy [16]. Smart building strategy is also a widespread topic for improving the energy performance, environmental awareness and occupant comfort in residential buildings [17-19]. Energy utilization from various sources such as geothermal heat energy and different mechanical systems were analysed in our previous researches [20, 21]. Economic evaluations are also a crucial part in demonstrating a feasibility study from the investment point of view [22].

An overall energy performance analysis with detailed economic evaluation for single family residential buildings is not yet elaborated for the climatic data of Slovenia. The research contributes to a detailed evaluation of single family residential buildings energetic and economic aspects under refurbishment procedures by formulating adequate energy efficient and cost-efficient solutions.

Financial opportunities for energetic reconstructions in Slovenia

A legal entity Eco Fund was established is Slovenia with the Ministry of the Environment and Spatial Planning. It is the only entity to get grants, also the loans interest rate is lower than in any commercial bank. The financial assistance is offered mainly through soft loans with low interest rates from revolving funds and through grants [23]. The main activities are:

– Loans to legal entitets for investments in enviromental infrastructure, energy efficiency, energy saving investments, and use of RES.
– Loans to individuals for conversion from fossil fuels to RES, energy saving investments, investments in water consumption reduction, connections to sewage system, small waste

water treatment plants, replacement of asbestos roofs
- Grants to individuals for investments in electric cars and for investments in residential buildings (energy efficiency and use of RES)
- Grants to legal entities for investments in electric cars and buses for public transport on compressed natural gas or biogas

There are eleven different proposes for grants to individuals, for example the grants for solar heating systems installation to residential buildings, heat pumps installation for central heating, energy-efficient wooden building fittings installation in older residential buildings, thermal insulation of facades older single- or two-family capacity, *etc*.

Energy-efficient wooden building fittings installation in older residential buildings [23]

Right for the grant for existing external building furniture replacement with a new energy-efficient wooden outer carpentry with the thermal transitivity of the $U \leq 1.1$[Wm^{-2}K^{1}]. The amount of non-refundable financial incentives is up to 20% of all investment costs, but not more than EUR 100 per m^2 of windows.

Heat pumps installation for central heating [23]

The amount of non-refundable financial incentives is up to 20% of the investment costs, but not more than 1000 EUR for the heat pump air to water.

Facades thermal insulation

There are the grants for facades system installation with at least 18 cm layer of thermal insulation, where the thermal conductivity of the thermal insulation is $\lambda \leq$ 0.045 [Wm^{-1}K^{-1}]. The thickness of the thermal insulation can also be smaller, but must fulfil the ratio $\lambda/d \leq 0.250$ [Wm^{-2}K^{-1}]. The amount of non-refundable financial incentives is up to 20% of the recognized investment costs, but not more than 12 EUR/m^2.

Energy demand analysis and evaluation with dynamic simulation

A dynamic energy simulation is a complex mathematical approach, which requires numerous input parameters in order to create an environment approximated to natural conditions. The interpolation of detailed hourly climate data is obligatory in the simulation, which is programmed to be

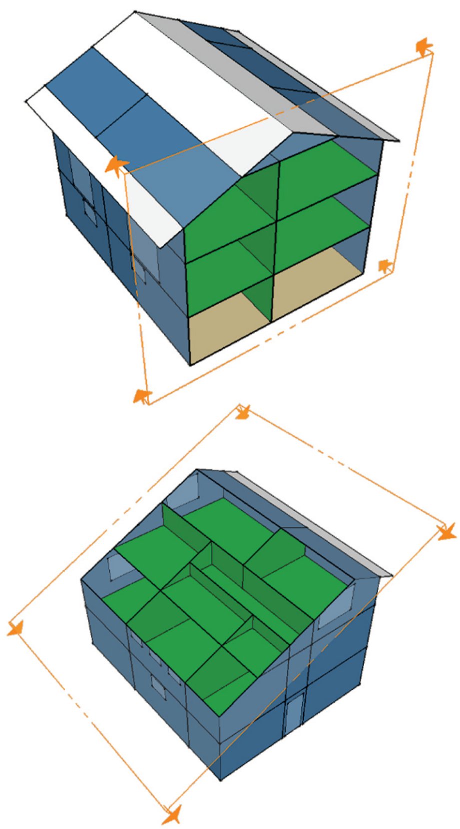

Figure 1. Residential building's multi-zone thermal model

conducted for an annual period in hourly time steps. The influence of each parameter can be investigated extensively and systematically utilizing a dynamic energy simulation engine as EnergyPlus, which allows flexibility of the thermal model and its properties.

Multi-zone thermal model construction

First of all, the building geometry was created in Sketchup [24] software with OpenStudio plug-in [25] according to the existing reference building's technical data (floor plan, section plan and construction data). The residential building's 3-D multi zone model can be seen in fig. 1. Floor plans of the building are shown in the Appendix. The multi-zone thermal model was divided into 10 thermal zones with the following properties as seen in tab. 1. The basement was not included in the thermal zones, since it is use for the garage and storage.

Table 1. Building zone summary

no.	Zone name	Area [m^2]	Volume [m^3]	Gross Wall Area [m^2]	Window Area [m^2]
1	Basement, garage	82.00	35.36	10.40	2.40
2	Bathroom and WC Ground floor	14.14	35.36	10.40	2.40
3	Bathroom WC 1. floor	14.14	30.90	6.24	0.75
4	Bathroom 1 1. floor	15.12	33.30	14.23	2.43
5	Bathroom 2 1. floor	17.02	38.58	15.98	2.43
6	Bathroom ground floor	15.12	37.80	19.50	3.96
7	Corridor and staircase 1. floor	14.84	34.80	13.64	2.43
8	Corridor and staircase ground floor	20.88	45.98	16.85	0.00
9	Living room 1. floor	14.84	37.09	16.63	2.43
10	Living room, kitchen and dinning room, ground floor	37.90	94.75	44.25	7.05
Total		246.00	593.55	248.71	26.13
Heated total		164.00	388.55	157.71	23.8
Unheated total		82.00	205.00	91.00	82.25

Dynamic simulation input parameters

Climate data

The input data process in the energy analysis workflow consisted of two phases. The first input parameter package was the building location and climate data. Climate data for the Location of Ljubljana was imported from the EnergyPlus software's Weather Data by Region database [4]. The weather data for Slovenia were used from the data packages of ASHRAE Climate Design Conditions [3] which are shown in tab. 2.

The location and weather data were imported from EPW data center [4], since the climate data needs to be converted into EPW extension file, importable into EnergyPlus for dynamic energy simulation. The location of the building is Ljubljana, Station 130140, N 46°13', E 14°28', Altitude = 385 m, standard pressure at elevation is 96,785 Pa. The imported weather data were design conditions from *Climate Design Data 2009 ASHRAE Handbook*. The ASHRAE design conditions are generated carefully from a period of record (typically 30 years) to be representative of that location and to be suitable for use in heating/cooling load calculation [3].

Table 2. Ljubljana/Brnik, Slovenia (wmo: 130140)

Lat: 46.22N		Long: 14.48W			Elev: 385		StdP: 96.78			Time zone:1.00			Period:82-06		
Annual heating and humidification design conditions															
Coldest month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB		
			99.6%			99%			0.4%		1%				
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
1	−13.2	−10.8	−16.2	1.0	−9.8	−13.9	1.2	−7.2	7.3	2.1	5.8	0.3	0.6	280	
Annual cooling, dehumidification, and enthalpy design conditions															
Hottest month	Hottest month DB range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
7	12.5	30.2	20.3	28.8	19.9	27.0	19.1	21.2	28.0	20.4	27.0	19.6	25.8	2.9	120
Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
19.0	14.5	24.2	18.1	13.6	22.9	17.2	12.9	22.1	63.4	28.2	60.6	27.1	57.7	25.8	913
Extreme annual design conditions															
Extreme annual WB			Extreme Max WB	Extreme annual DB				n-year return period values of extreme DB							
				Mean		Standard deviation		*n* = 5 years		*n* = 10 years		*n* = 20 years		*n* = 50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
6.1	5.1	4.2	25.5	-16.9	32.7	3.4	1.7	-19.3	33.9	-21.3	34.8	-23.2	35.8	-25.7	37.0
Monthly climatic design conditions															
			Annual	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature, degree - days and degree - hours		T_{avg}	9.4	−1.3	0.3	4.7	9.0	14.1	17.4	19.7	19.2	14.9	10.4	4.1	−0.2
		Sd		4.37	4.23	3.87	3.24	3.05	3.28	2.77	2.91	3.01	3.66	4.40	4.28
		HDD10.0	1389	352	272	167	56	4	0	0	0	2	40	182	315
		HDD18.3	3401	610	505	422	280	133	55	18	24	107	245	427	573
		CDD10.0	1179	0	0	3	26	133	223	301	287	149	53	4	1
		CDD18.3	149	0	0	0	0	3	28	61	52	6	0	0	0
		CDH23.3	1614	0	0	0	3	77	321	625	528	61	1	0	0
		CDH26.7	421	0	0	0	0	7	77	178	154	4	0	0	0
Monthly design dry bulb and mean coincident wet bulb temperatures		0.4%	DB	10.1	14.2	19.9	23.0	27.2	31.1	32.8	32.1	27.1	22.4	16.0	11.9
			MCWB	7.6	8.1	10.8	13.1	17.5	20.6	20.6	20.6	19.1	16.2	13.0	10.0
		2%	DB	8.1	11.0	16.4	20.2	25.2	29.0	30.2	30.1	25.1	20.0	13.9	9.8
			MCWB	6.3	6.4	9.9	12.4	16.2	20.0	20.5	20.3	18.2	15.5	11.9	8.4
		5%	DB	6.4	8.8	14.0	18.2	23.8	27.0	28.8	28.2	23.2	18.0	12.1	7.5
			MCWB	4.9	5.6	8.5	11.3	15.7	18.9	19.9	19.7	17.3	14.2	10.3	6.6
		10%	DB	4.8	6.8	11.9	16.1	21.9	25.0	27.0	26.2	21.2	16.1	10.8	5.8
			MCWB	3.4	4.1	7.6	10.2	14.6	17.7	19.3	18.9	16.3	13.3	9.5	5.0
Monthly design wet bulb and mean coincident dry bulb temperatures		0.4%	WB	8.7	8.9	12.2	14.8	18.7	21.8	22.7	22.2	20.0	17.3	13.5	10.4
			MCDB	9.2	12.3	17.4	21.0	25.2	28.3	29.6	28.8	24.9	21.1	15.4	11.9
		2%	WB	6.7	7.5	10.4	13.0	17.2	20.6	21.3	21.1	18.7	16.0	12.1	8.6
			MCDB	7.7	10.1	15.0	18.8	23.5	27.4	28.1	28.0	23.5	19.2	13.5	9.4
		5%	WB	5.2	5.9	9.3	12.0	16.2	19.5	20.5	20.2	17.9	14.8	10.9	6.5
			MCDB	6.2	8.2	13.1	17.2	22.0	25.9	27.1	26.8	22.4	17.1	12.1	7.1
		10%	WB	3.5	4.2	8.1	10.9	15.2	18.3	19.6	19.4	16.9	13.9	9.7	4.8
			MCDB	4.3	6.1	11.5	15.2	20.6	23.9	25.8	25.4	20.7	15.9	10.6	5.2
Mean daily temperature range			MDBR	7.3	9.6	10.7	11.1	12.2	11.6	12.5	12.0	11.0	9.5	7.0	6.1
		5% DB	MCDBR	9.4	13.1	15.7	15.9	16.2	15.2	15.4	15.4	13.8	11.9	8.8	7.7
			MCWBR	7.2	8.9	9.5	8.6	8.0	7.1	6.8	6.8	7.5	7.4	6.4	6.1
		5% WB	MCDBR	8.2	11.9	13.6	14.0	14.5	14.3	14.3	14.1	12.6	10.3	7.3	6.7
			MCWBR	6.7	8.5	8.6	7.9	7.5	6.9	6.9	6.8	7.5	7.4	6.4	6.1
Clear sky solar irradiance		TauB		0.317	0.351	0.422	0.442	0.442	0.454	0.449	0.441	0.411	0.383	0.342	0.322
		TauD		2.340	2.131	1.914	1.906	1.971	1.980	2.030	2.053	2.118	2.150	2.277	2.346
		Ebn_{noon}		774	806	788	813	827	818	816	806	796	758	729	723
		Ebn_{noon}		87	122	167	182	176	175	165	156	136	117	91	80

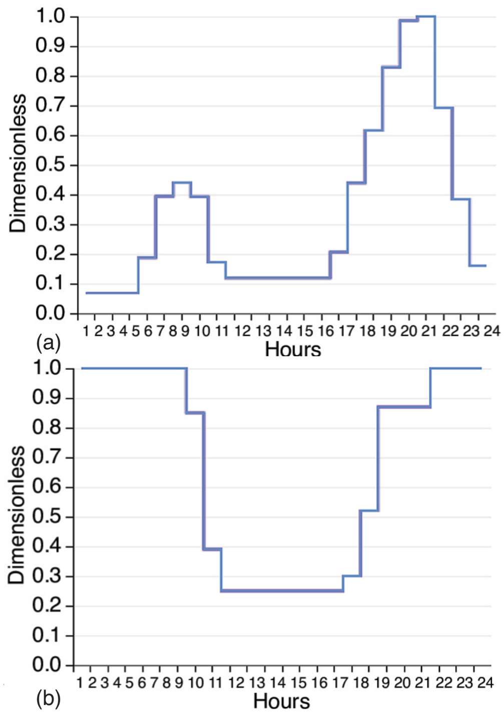

Figure 2. Schedules for electric lighting (a) and occupancy (b)

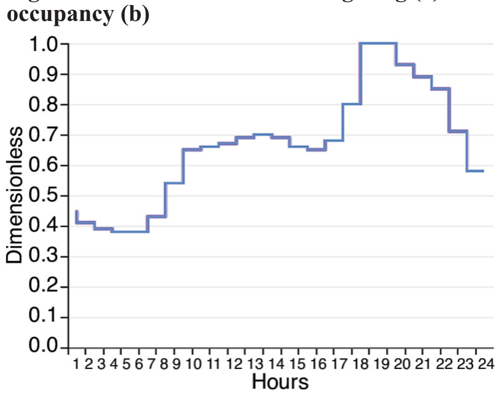

Figure 3. Schedules for electric equipment

Internal heat loads

Each thermal zone was assigned with internal load properties typical for a single-family residential building according to the ASHRAE 90.1 standard [1] (mid-rise apartment), from which selected schedules were adopted which are typical for all residential buildings such as occupancy schedules, occupant activity and occupant gains, and electric lighting schedules as seen in fig.2 and 3.

The average air change rate equal to 0.5 ach, lighting, and electric equipment gains were formulated according to Hungarian 7/2006 TNM energy efficiency regulation [26]. The thermal zones were determined according to their function in the building, as shown previously in tab.1. The internal zone loads were set to typical single-family residential building loads considering occupancy (120 W per person, including four persons), electric equipment (total 4500 W for electric appliances in kitchen and laundry, and 150 W for computer), lighting (5 [Wm^{-2}]). Considering building construction, 29 cm thick clay block exterior walls were applied, with reinforced concrete slabs and floor construction. Window's thermal transmittance values were imported according to pre-refurbishment and post-refurbishment. In total six scenarios with various expanded polystyrene thermal insulation thicknesses for exterior walls and roof were simulated. The energy demands for heating and cooling were compared on an annual basis and per unit floor area respectively. The following tab. 3 demonstrates the building envelope's U-values for the simulated scenarios.

Table 3. Simulated building construction scenarios

Building envelope scenario	EPS insulation thickness [cm]	Exterior wall *U*-factor [$Wm^{-2}K^{-1}$]	Roof *U*-factor [$Wm^{-2}K^{-1}$]	Window	
				U-factor [$Wm^{-2}K^{-1}$]	SHGC
1	0	1.91	2.23	3.5	0.87
2	0	1.91	2.23	1.1	0.45
3	5	0.47	0.49	1.1	0.45
4	10	0.28	0.29	1.1	0.45
5	15	0.20	0.21	1.1	0.45
6	20	0.15	0.16	1.1	0.45

Heating and cooling energy demands

The heating and cooling energy demands were calculated on an annual basis in hourly time steps, in total 8760 hours. The thermostat schedules were set according to the following date, time intervals and indoor air temperature levels as shown in tab. 4.

Table 4. Thermostat schedules

Schedule	Date	Time	Indoor air temperature
Heating setup schedule	May 1 to September 30	Monday to Sunday 7-23 hours	min 21 °C
		Monday to Sunday 23-7 hours	min 18 °C
Cooling setup schedule	October 1 to May 1	Monday to Sunday 7-23 hours	max 26 °C
		Monday to Sunday 23-7 hours	No control

The simulation was performed according to the heat balance calculations method used in the EnergyPlus simulation engine. Detailed description of the heat balance model, calculation method of the heat losses and adaptive comfort model by the software developers is described in detail in the EnergyPlus Engineering reference [27]. Simulated annual heating and cooling demands of the six scenarios clearly described in tab. 3 are presented in tab. 5.

Table 5. Annual heating and cooling energy demand

No.	EPS insulation thickness [cm]	Heating demand [kWhm^{-2}a^{-1}]	Cooling demand [kWhm^{-2}a^{-1}]	Total heating demand [kWh/a]	Total cooling demand [kWh/a]
1	0	162	14	26667	2222
2	0	141	9	23124	1476
3	5	64	11	10496	1804
4	10	47	13	7708	2132
5	15	40	14	6560	2296
6	20	36	15	5904	2460

According to the very low annual cooling demand, it was concluded that an air conditioning system would not be feasible in these cases. The cooling of the building in a short specific summer period can be solved by passive ventilation or night time flush out of the building. As concluded from the energy demand values the cooling energy demand is increasing in the function of building envelope's higher thermal performance (higher thermal insulation thickness), since the generated heat from appliances, occupants and solar gains remain in the thermal zones.

Results of the energy performance simulation and evaluation of the heating system

The heating system was modeled and its performance was simulated on an annual basis in order to assess a detailed insight into the energy demands of the three analyzed heating systems. In fig. 4 the radiant hot water loops are presented. The left radiant hot water loop was applied for the oil boiler (OB) water heater and the gas boiler (GB) water heater, where both systems loops are identical. The right radiant hot water loop presents the heat pump water heater loop. All three systems have a variable speed pump (VSP), set point manager according to heating schedule and entering hot water temperature control. The availability of the radiant system was 18 hours per day from 6-24 hours during the six month heating season, starting from the 15th of October until the middle of April. In all three heating systems the water tanks were situated in the basement of the building. The COP of the oil and GB was set to 0.9, and for the air to water heat pump (AWPH) system, it was set to 2.5.

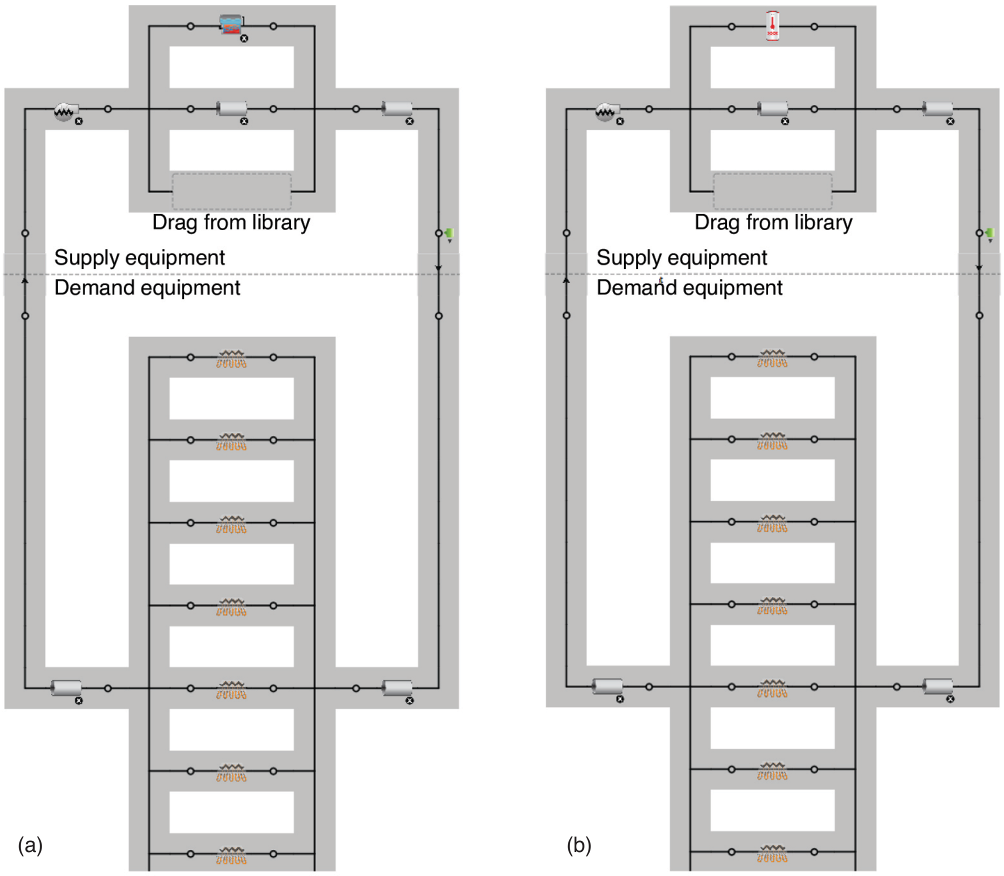

Figure 4. Radiant hot water loop with OB water heater (a), radiant hot water loop with GB water heater (left-identical), radiant hot water loop with AWHP water heater (b)

The results of the simulations are presented in tab. 6 where the simulated three heating system's energy demands are compared per square meter unit area. The annual heating system also contains the VSP electricity demand. The energy demands of the systems are also converted into primary energy. The conversion factor for electricity was 2.5, for gas 1 and for oil 1.

The economic evaluation will show precisely, which of the following insulation thicknesses would be the most cost efficient while maintaining efficient energy performance of the building.

Table 6. Heating system energy use unit square meter of floor area

Radiant heating system	Annual heating energy demand [kWhm^{-2}a^{-1}]	Annual heating system energy demand per unit [kWhm^{-2}a^{-1}]	Primary energy demand per unit area [kWhm^{-2}a^{-1}]
Oil boiler water heater		41.52 OB + 2.22 VSP	47.07
Gas boiler water heater	40	42.70 GB + 2.22 VSP	48.25
Air to water heat pump water heater		16.90 AWHP + 2.22 VSP	47.80

Results of the economic analyses

The energy demands for different energetic reconstructions of single-family residential buildings in Slovenia were compared according to the economic results. The following assumptions and data were considered during the economic analysis:

- the individual house is without thermal insulation,
- the house currently uses heating OB for heating purposes, with an efficiency of 0.9, or GB with an efficiency of 0.9,
- the calorific value of heating oil is 10 kWh/L,
- prices of electricity, heating oil and natural gas are 0.1 EUR/kWh [28], 0.835 EUR/L [29] and 0.045 EUR/kWh [30], respectively,
- the discount rate is 4%,
- the prices are different for the facade of walls and the roof, and
- the subsidies are included in accordance with part 2.

Different energy efficient reconstruction options were presented and the heating demands, presented in tab. 4 were calculated. Heating demands are presented as delivered energy. Based on the results an economic evaluation was performed.

Windows and thermal insulation

The single-family building's exterior wall area is 248.71 m^2, roof area is 86 m^2 and window area is 26.7 m^2. The investment into new windows with U = 1.1 [Wm^{-2}K^{-1}] is 3204 EUR, where the subsidies of 20% of total investment are taken into account. The heating costs and savings were evaluated according to calculated heating demand, for the house with different insulation thickness and at the first stage a widow replacement, as shown in tab. 7. The investment costs for different insulation thickness are presented in tab. 8.

Table 7. The heating costs and savings for different insulation thicknesses if the house is heated by heating oil or natural gas

	Scenario	EPS insulation [cm]	Total heating demand [kWh/a]	Heating oil		Natural gas	
				Costs [EUR/a]	Savings [EUR/a]	Costs [EUR/a]	Savings [EUR/a]
Old windows	1	0	26667	2449	–	1320	–
New windows	2	0	23124	2124	325	1,145	175
	3	5	10496	964	1485	520	800
	4	10	7708	708	1741	382	938
	5	15	6560	603	1847	325	995
	6	20	5904	542	1907	292	1,028

Table 8. The investment costs for roof and walls for different EPS thickness

Scenario	EPS insulation [cm]	Roof		Walls		Total investment [EUR]	Subsidie for facade [EURm^{-2}]	Final investment including windows [EUR]
		Price [EURm^{-2}]	Investment [EUR]	Price [EURm^{-2}]	Investment [EUR]			
3	5	6.2	533	33	8207	8741	0	11945
4	10	9.5	817	35	8705	9522	0	12726
5	15	12.6	1.084	37	9202	10286	2,057	11433
6	20	15.7	1.350	42	10446	11796	2,359	12641

The investments were evaluated with net present value (NPV) method and the payback period was determined if the house is heated with OB or by natural GB. The results are presented in figs. 5 and 6 and tab. 9. The NPV were calculated in comparison with the first scenario considering previously mentioned data and assumption.

The differences in NPV can be observed if the building is heated by natural gas or by heating oil, while the costs for heating oil are much higher and for that case savings are larger and the payback periods are shorter, than for the natural gas heating.

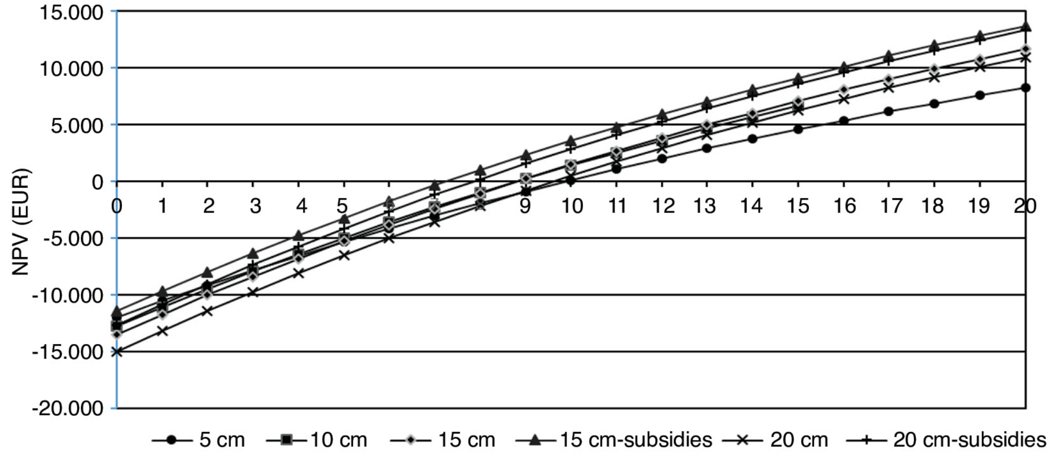

Figure 5. The NPV for different EPS insulation thickness – heating oil

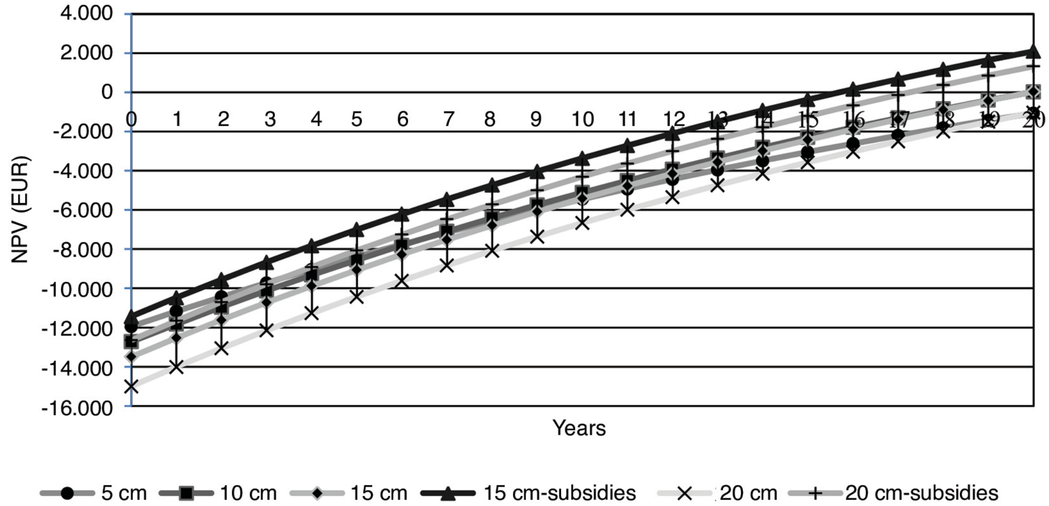

Figure 6. The NPV for different EPS insulation thickness – natural gas

Radiant floor heating

The reference single-family residential building has radiator heating. The calculations were performed if radiant floor heating would be installed. The results are presented on fig. 7, for the case if the windows are replaced and the house is insulated with 15 cm EPS.

The investment costs for radiant floor heating are approximately 40 [EURm^{-2}] and the house has 164 m^2 of the floor area, where the heating will be installed. The investment for heating reconstruction is 6,560 EUR, and if the investment from section *Windows and thermal insulation* are included, total investment costs are 17,933 EUR. On the other hand, the savings increase because the efficiency ratio for radiant floor heating is 1.5 and the entire savings from section *Windows and thermal insulation* and section *Radiant flour heating* are 3694 EUR/a for heating OB and 2099 EUR/a for GB. The payback periods are for heating oil boiler 4 years and for GB 8 years.

Table 9. Payback period for different EPS insulation thickness

EPS insulation thickness [cm]	Subsidies	Payback period - heating oil (a)	Payback period - natural oil (a)
5	no	9	more than 20 years
10	no	8	19
15	no	8	19
15	**yes**	**7**	**15**
20	no	10	more than 20 years
20	yes	7	17

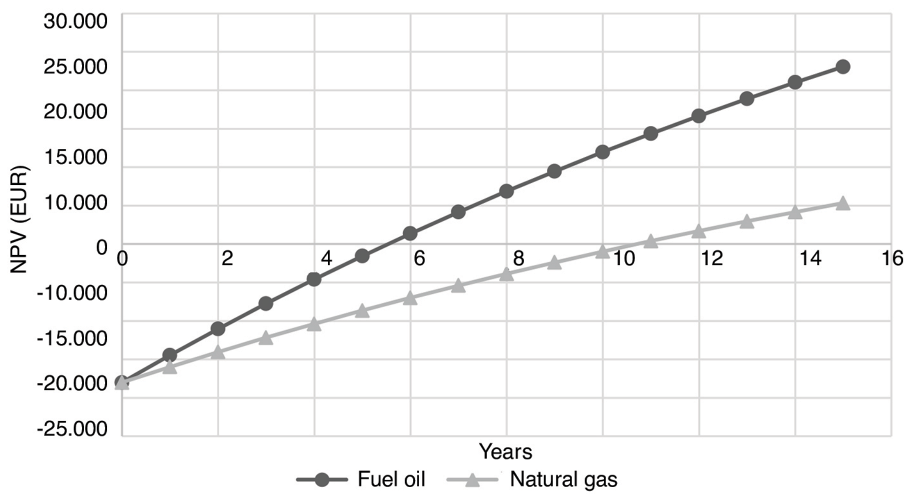

Figure 7. The NPV for radiant floor heating including the investment for 15 cm EPS insulation and windows - heating oil and natural gas

Air to water heat pump

The AWHP have in many cases efficient performance for heating of single-family houses. The heat pump with 11 kW where chosen for the base house heating with new windows, reconstructed façades and the radiant floor heating. The investment costs for such heat pump are 10000.00 EUR with a COP of 2.5. The electricity consumption for such heat pump including boiler and secondary pump was 19.12 [$kWhm^{-2}a^{-1}$]. The payback periods are for heating OB and GB 6 years and 12 years, respectively. The NPV for the entire investment in case of heating oil and natural gas is presented on fig. 8.

The annual operating costs for three different heating systems are presented in tab. 10.

The optimal solutions from the annual costs point of view differ depending on if the house is heated by oil or by natural gas, because the price of heating oil is 0.0835 EUR/kWh and the price for natural gas is 0.045 EUR/kWh. The findings have contributed to better understanding of operating costs and have encouraged the selection of appropriate investment.

Table 10. Annual operation costs for different heating systems

Heating system	Annual operation costs [EUR/a]
The OB water heater	603
The GB water heater	325
The AWHP water heater	314

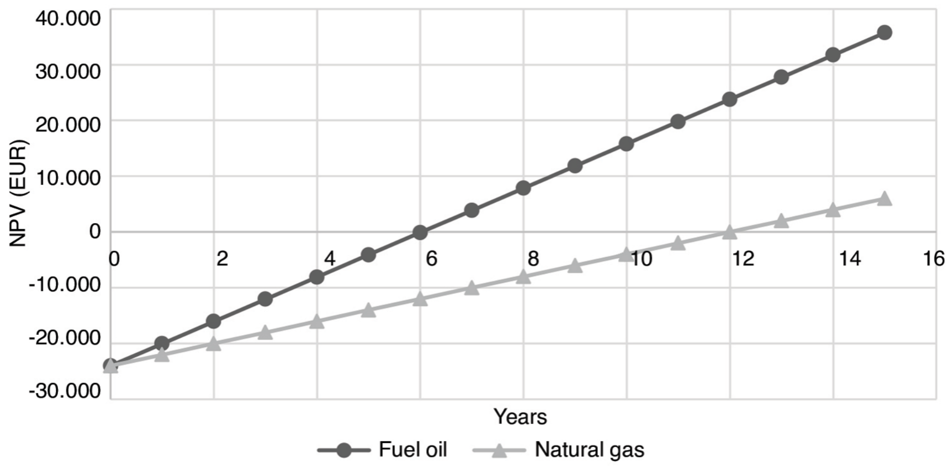

Figure 8. The NPV of heat pump including the investment for 15 cm EPS insulation, windows and radiant floor heating - heating oil and natural gas

In conclusion, heating system efficiency does not always contribute to economic benefits, the research has highlighted that the heat pump with COP 2.5 and the GB with COP 0.9 will have practically identical annual operation costs, of approximately 320 EUR. If environmental performance is considered for these systems, it was calculated that the primary energies were also identical (with slight deviation of 0.9%). Considering the appropriate selection, the only selective parameter would be the investment costs, which depends from the heating systems' manufacturer and installation.Further research will include the energy and economic analysis of multi-family residential buildings and commercial office buildings. The economical aspect is highly important when improving the thermal properties of building envelope. Materials and construction expenses will be taken into consideration according to the performance and investment aspect of an ongoing project.

Financial point of view

The financial analyses were performed for different scenarios according to energy audit requests. It was assumed that the energy use is optimized and correctly used. Two different base cases were compared, because in many area natural gas is not available, and the heating oil is used for heating. It was assumed that the house had radiator heating, the windows were old with U around 3.3 $Wm^{-2}K^{-1}$ and without insulation. The heating costs were calculated according to energy heat demands and the costs per year were for heating oil and natural gas 2449 EUR and 1320 EUR. The investment into new windows and façade with 15 cm of EPS will be returned after seven years for heating oil and after 15 years for gas. The second scenario was evaluated if the radiator heating is replaced with radiant floor heating with efficiency ratio of 1.5 comparing to radiator heating. The payback periods were short and for heating oil was four years, for natural gas it was eight years. At the end, the replacement of heating system with air-water heat pump was evaluated, and the payback time was a little bit longer, for heating oil six years and for gas 12 years.

Conclusion

The formulated methodology is applicable for various individual house types for the same climate conditions. According to the determined best-case scenario it would be most appropriate from the energetic and economic point of view to apply 15 cm of EPS thermal insulation and windows with 1.1 [$Wm^{-2}K^{-1}$]. The low temperature radiant floor heating system was selected due to its higher efficiency according to the radiator system. It is most preferable application would be if it is connected to an air source heat pump water heater with an average COP of 2.5. If primary energy consumptions are compared it can be concluded that all three systems require the same amount of energy. Nevertheless, heating system efficiency does not always contribute to economic benefits, the research has highlighted that the system with higher COP will have practically identical annual operation costs. Considering the appropriate selection, the only selective parameter would be the investment costs.

According to financial analyses the optimal scenario includes the replacement of on if the house is heated by oil or by natural gas, because the price of heating oil is 0.0835 EUR/kWh and the price for natural gas is 0.045 EUR/kWh. The findings have contributed to better understanding of operating costs and have encouraged the selection of appropriate investment.

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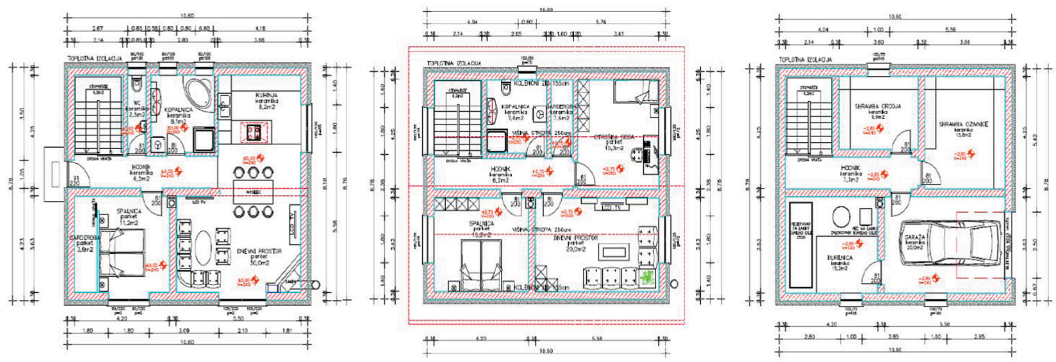
Appendix

Floor plans of the single family residential building



Ground floor First floor Basement

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