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THE MULTICRITERIA ASSESSMENT MODEL FOR AN ENERGY SUPPLY SYSTEM OF A LOW ENERGY HOUSE

Rasa DŽIUGAITĖ-TUMĖNIENĖ, Vilūnė LAPINSKIENĖ

Department of Building Energetics, Vilnius Gediminas Technical University,
Saulėtekio al. 11, LT-10223 Vilnius, Lithuania

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Abstract. Researches on efficient energy supply in new buildings are significant for implementation of energy performance targets for buildings, aiming to increase energy efficiency as well as the share of renewable energy in the total balance of consumed energy and to reduce greenhouse gas emissions to the environment. Many studies suggest integrated assessment methods that combine building energy simulation and optimization methods. However, optimal solutions for case studies are based only on quantitative criteria (energy technical, environmental and economic). Therefore, such an approach is not sufficient to achieve the optimal building energy supply system in respect of the quantitative and qualitative criteria.

The presented multicriteria assessment model for an energy supply system of a low energy house allows determining the optimal combination of technologies for a building energy supply system (BESS). Six variants of building constructions and fifteen combinations of BESS for each variant were analysed. Energy efficiency, environmental impact, economic rationality, comfort and system functionality were considered key criteria for optimal decision making. The results showed that the optimal solution for low energy and passive houses in Lithuania and other cold climate countries is the building envelope that corresponds to characteristics of energy efficiency class A+ and the BESS combination, consisting of a wood boiler and electricity from the national electricity grid.

Keywords: low energy building, energy supply system, DesignBuilder, Polysun, WASPAS.

Introduction

Over the past decade, the European Union (EU) has been facing unprecedented energy challenges resulting from increased import dependency, concerns over supplies of fossil fuels worldwide and a clearly discernible climate change. In spite of this, Europe continues to waste at least 20% of its energy due to inefficiency. In recent years, energy efficiency has improved considerably; however, it is still technically and economically feasible to save at least 20% of total primary energy (European Parliament and Council 2010). Partly because of its large share of total consumption, the largest cost-effective savings potential lies in the residential (household) sector and commercial buildings (tertiary) sector, where the full potential is now estimated to be around 27% and 30% of energy use, respectively (Commission of the European Communities 2011). EU residential buildings have the greatest impact on the environment and contribute to about 77% (725 Mt/year) of carbon dioxide (CO_2) emissions, while non-residential buildings determine the remaining 23% of pollutants to the environment. Single-family houses make up the largest group of EU residential sector, which causes about 60% of total CO_2 emissions (435 Mt/year) (Hamdy *et al.* 2011). Therefore, it is necessary to exploit the unrealised potential of energy savings in individual residential buildings by determining the cost-optimal levels of energy performance of build-

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Corresponding author:
R. Džiugaitė-Tumėnienė E-mail: *rdziugaite@yahoo.com*

ings and increasing the number of nearly zero-energy buildings. It should be noted that Lithuania has no national indicators for the primary energy demand of buildings and greenhouse gas emissions, which motivate the extent of energy use from renewable energy resources, the reduction of environmental impact and the improvement of energy efficiency in buildings. The main factors influencing building energy demand are: climatic conditions; indoor thermal comfort conditions; thermal, architectural and structural features of a building; air-tightness of the building envelope; operating mode of the building; and engineering systems. Therefore, the feasible combinations of energy efficient measures for building envelope and energy supply systems have to be evaluated in order to reach the optimal energy efficiency level of the building. However, during the complex evaluation of building energy efficiency, a large number of parameters and interrelated variables are obtained, which influence the final level of the building's energy efficiency (Diakaki *et al.* 2008). Consequently, it is difficult to find an optimal set of energy efficiency-related measures by using the best practice and the traditional selection approaches (Machairas *et al.* 2014; Luna-Rubio *et al.* 2012). Recently, the development of methods for integrated evaluation of building energy performance has increased. These methods combine the building energy modelling and different optimization techniques, in order to reduce the search for the optimal solution, provide a clear and informative final result (Dufo-López, Bernal-Agustín 2009; Hamdy *et al.* 2013; Ihm, Krarti 2012; Kayo, Ooka 2010; Magnier, Haghihat 2010; Ooka, Komamura 2009).

This article presents the integrated assessment for the optimal energy supply system of a low energy house, combining modelling of the building and its energy supply system with the decision making method. The objective of this research is to determine the optimal solution of the building energy supply, considering energy, ecological, economic, comfort and system functionality criteria.

1. Methodology

In this paper, the algorithm of the multicriteria assessment model for a building energy supply system is used in order to determine the optimal combination of technologies of building energy supply system (BESS) considering energy, environmental impact, economic, comfort and functionality criteria (Fig. 1).

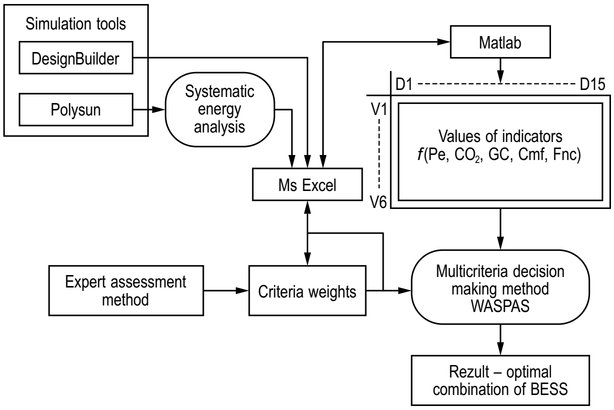

Fig. 1. The algorithm of the multicriteria assessment model for a building energy supply system

The developed method provides detailed analysis of a building's energy consumption and possible combinations of energy supply systems, to make a rational solution according to selected criteria (energy efficiency, environmental impact, cost, comfort and functionality). In this case study, the energy modelling tool DesignBuilder was used to determine the building energy demand (EnergyPlus Energy Simulation 2013). Selected combinations of technologies for a building energy supply system (see Table 1) were modelled using the modelling tool PolySun (Polysun 2000).

Table 1. Selected combinations of technologies for the energy supply system of a building

Firewood	D1	Wood boiler (WB)
	D2	Wood boiler, solar collectors (SC)
	D3	Wood boiler, solar collectors, solar cells (PV)
Pellets	D4	Pellet boiler (PB)
	D5	Pellet boiler, solar collectors
	D6	Pellet boiler, solar collectors, solar cells
Natural gas	D7	Condensing gas boiler (GB)
	D8	Condensing gas boiler, solar collectors
	D9	Condensing gas boiler, solar collectors, solar cells
Electricity	D10	Air–water heat pump (HP$_{\text{air–water}}$)
	D11	Air–water heat pump, solar collectors
	D12	Air–water heat pump, solar collectors, solar cells
	D13	Ground–water heat pump (HP$_{\text{ground–water}}$)
	D14	Ground–water heat pump, solar collectors
	D15	Ground–water heat pump, solar collectors, solar cells

Results of the simulation of BEES combinations were processed by using the systematic energy analysis. The energy analysis of different subsystems (emission, distribution, storage, generation) pertaining to selected combinations of building energy supply system was performed according to EN 15316-1. Losses and energy performance factors of building energy systems were identified. Matlab and MS Excel computer programmes were used for data processing and analysis of output results from modelling programs.

The multicriteria decision making method WASPAS was chosen to evaluate combinations of technologies pertaining to a building energy supply system (Zavadskas *et al.* 2012). WASPAS method calculations were carried out using equations (1), (2), (3), (4), (5), which can be described as follow:

– normalized values for WASPAS method:

$$\bar{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}}, \tag{1}$$

where $i = \overline{1,m}$; $j = \overline{1,n}$, if optimal value is min;

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \tag{2}$$

where $i = \overline{1,m}$; $j = \overline{1,n}$, if optimal value is max;

– weighted and normalized values for the summarized part of WASPAS method:

$$\bar{\bar{x}}_{ij,sum} = \bar{x}_{ij}\, q_j, \tag{3}$$

where $i = \overline{1,m}$; $j = \overline{1,n}$;

– weighted and normalized values for the multiplication part of WASPAS method:

$$\bar{\bar{x}}_{ij,mult} = \bar{x}_{ij}^{\,q_j}, \tag{4}$$

where $i = \overline{1,m}$; $j = \overline{1,n}$.

The final results of WASPAS calculation are carried out with this equation:

$$\mathrm{WPS}_i = 0.5\sum_{j=1}^{n} \bar{\bar{x}}_{ij} + 0.5\prod_{j=1}^{n} \bar{\bar{x}}_{ij}, \tag{5}$$

where $i = \overline{1,m}$; $j = \overline{1,n}$.

The weights of each criterion (x_1 – energy, x_2 – ecological, x_3 – economic, x_4 – comfort, x_5 – functionality) were determined using the expert assessment method. The experts filled in 28 questionnaires to assess the significance of each criterion according to the rating scale. Criteria weights (q_j) were calculated using the AHP (Analytic Hierarchy Process) pairwise comparison method (Saaty, Erdener 1979; Podvezko 2009). Criteria weights determined according to the results of questionnaires and the pairwise comparison method are presented in Table 2.

Table 2. The pairwise comparison of criteria weights (q_1, q_2, q_3, q_4, q_5)

	x_1	x_2	x_3	x_4	x_5	Σ	q
x_1		1.19	1.02	0.94	0.96	4.116	*0.204*
x_2	0.8		0.83	0.77	0.78	3.224	*0.160*
x_3	1.0	1.2		0.94	0.96	4.073	*0.202*
x_4	1.1	1.3	1.1		1.02	4.449	*0.220*
x_5	1.0	1.3	1.0	1.0		4.344	*0.215*
			Σ			20.206	1.000

After identification of criteria weights, the initial decision making matrix was formed with the help of the computer programme Matlab for further multicriteria analysis using method WASPAS. The initial decision making matrix contains simulation results for 15 combinations: primary energy demand, CO_2 emission, global cost, the level of comfort and system functionality; the criteria and weights for all these indicators. The result of multicriteria evaluation is the optimal combination of technologies of a building energy system.

2. Case study

In order to show the application of the introduced BESS model, the assessment of a low energy house with 6 different construction types and 15 combinations of BESS technologies is presented.

2.1. Theoretical model of energy balance in a low energy building

In this case, the research object is an existing individual low energy house, located in Vilnius (Fig. 2). A theoretical building model was created by DesignBuilder, based on engineering data and architectural plans of the building.

Architectural and constructional solutions. The single family house has one floor with the total heated area of 160.24 m^2 and the volume of 480.72 m^3. The main facade is oriented to north-east. The house is divided into three zones: a living-dining room, kitchen and bedrooms with auxiliary premises. The ratio of window-to-wall is 16%, the biggest glazed facade of 17.5 m^2 is in the south facade. The structural system of the house is a residual formworks system from polystyrene foam blocks. The polystyrene foam blocks are

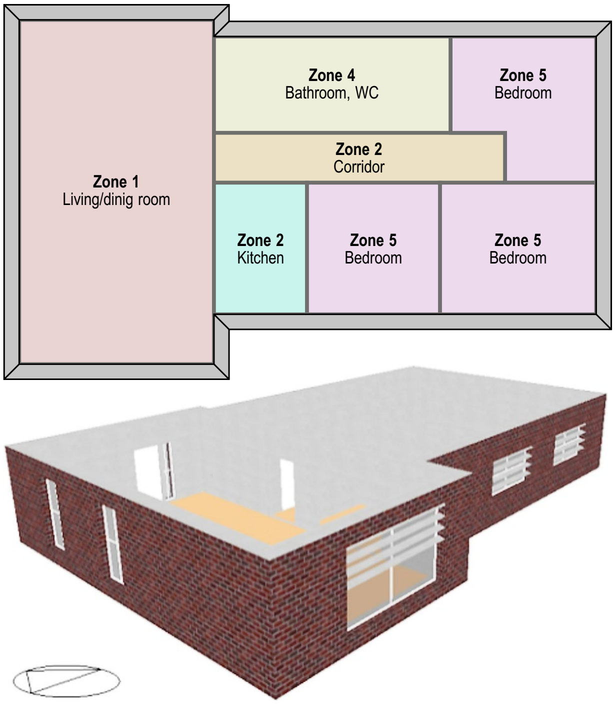

Fig. 2. Plan of the low energy house (the research object)

composed of hollow blocks, which are interconnected tightly and have formed connections on the connecting surface. During construction works, the inner cavity of hollow blocks was reinforced using reinforcement bars and filled with fluid concrete mixture. This case study presents six different construction types (from V1 to V6) for the house, where the extra insulation of polystyrene foam slabs is foreseen on the exterior facades.

The heat transfer coefficients of building construction variants are presented in Table 3. The heat transfer coefficients of the building elements and solar heat gain coefficients of windows are the main parameters, causing the biggest impact to the building energy demand.

Location and climatic data. Building energy modelling was performed using climatic data of Kaunas. Weather data was taken from IWEC (*International Weather for Energy Calculations*) database (IWEC 2009). The design outdoor air temperature for heating and cooling design was adopted −19.3 °C.

Occupancy profiles. Building energy modelling, performed by DesignBuilder, was performed according to typical occupancy profiles for weekdays, weekends and holidays. The following assumptions were made: two adults and three children live in the house; residents are not at home from 10 a.m. up to 5 p.m. on working days. The surplus heat from people and household electrical appliances was set according to the occupancy schedule. For simulation, the following heat flux densities were used: 3.06 W/m^2 in the dining room, 30.28 W/m^2 in the kitchen, 3.58 W/m^2 in the bedroom area.

Comfort. Different indoor temperatures are maintained in the separate building zones. During a heating season, indoor temperature is 22 °C in the dining room, 21 °C in the kitchen and bedrooms, 22 °C in the bathroom and shower room, 20 °C in the corridor. During summer, the comfort indoor temperature is assumed to be 26 °C. The assumption was made that the temperature increase of 2 °C is allowed and would not cause discomfort.

The indoor air quality is maintained using the mechanical ventilation system (v.s.) with heat recov-

Table 3. The main characteristics of building envelope elements

The variants of building constructions			V1	V2	V3	V4	V5	V6
Heat transfer coefficients of the building envelope corresponds to the energy efficiency class (STR 2.01.09:2012)			B			A	A+	A++
Geometry	Area	m^2	160.24					
	Volume	m^3	480.72					
	Orientation	°	ŠR					
Building elements	U_{IS}	W/m^{2}K	0.18	0.15	0.12	0.11	0.10	0.06
	U_{ST}	W/m^{2}K	0.13	0.13	0.10	0.09	0.08	0.06
	U_{GR}	W/m^{2}K	0.15	0.15	0.14	0.12	0.10	0.06
	U_L	W/m^{2}K	1.0	0.8	0.8	0.8	0.70	0.51
	Thermal bridges	W/mK	0.05	0.05	0.05	0.05	0.03	0
	Infiltration	h^{-1}	0.05	0.05	0.05	0.05	0.05	0.05
	Passive sun protection measures		External blinds on south-facing windows					
	Solar heat gains coefficient g		0.67	0.6	0.55	0.55	0.5	0.5

ery with 85% temperature efficiency. The plate heat exchanger is foreseen in the supply and exhaust ventilation unit. The same ventilation system is foreseen in all the combinations of BESS (from D1 to D15). Supplied and returned air amount is 190 m^3/h. The air change of 0.4 h^{-1} is ensured in the premises. In accordance to energy modelling results, the seasonal energy efficiency ratio of ventilation unit with heat recovery is 57%.

Operation mode of building engineering systems. In the case study, underfloor heating systems are foreseen. The temperatures of supply and return medium are 40 °C and 35 °C. The heating system is equipped with a control set of internal temperature change. During the heating season (from October to April) on working days from 10 a.m. to 5 p.m., the indoor temperature reduction of 2 °C is provided.

The assumption was made that the mechanical ventilation system would work one hour before occupants come back home and during the time of their presence. During the heating season, the supplied air temperature is 20 °C. During absence time (from 10 am to 4 pm), the ventilation system is turned off.

The decision to install the passive sun protection measures was made after the analysis of modelling results of the first building construction type (V1). The external blinds were foreseen on the southern facade for all building construction variants (from V1 to V2) in order to avoid the mechanical cooling system. The modelling results showed that the indoor temperature reaches 27 °C with installed external blinds. The mechanical cooling system is not provided in this case study.

Building energy demand for domestic hot water. The case study presents a typical single family detached house with two adults and two children. The energy demand for domestic hot water (DHW) preparation is 4110 kWh/a, when the average temperature of cold water is assumed to be variable. The average DHW consumption is 50 litres per person per day. Therefore, the building energy supply system is designed to provide 200 l of hot water per day at 55 °C for a single family house.

Building energy balance. The energy demand for heating, ventilation, domestic hot water, lighting and household appliances are evaluated in the energy balance of the low energy house.

The heat balance of the house is presented in Figure 3. The heat demand for domestic hot water (25.6 kWh/m^2a) and ventilation (13.2 kWh/m^2a) are the same for all building construction variants. The highest heat demand for space heating (35.5 kWh/m^2a) is obtained in case of V1. However, it could be decreased to 14.7 kWh/m^2a if the variant V6 is chosen.

Figure 4 presents the energy balance of the house, where the electricity energy demand for ventilation, lighting and household electrical appliances is evaluated. The electricity energy demand for circulation pumps of BESS is evaluated separately, because each combination of technologies of BESS generates the different electricity demand. Therefore in this case study,

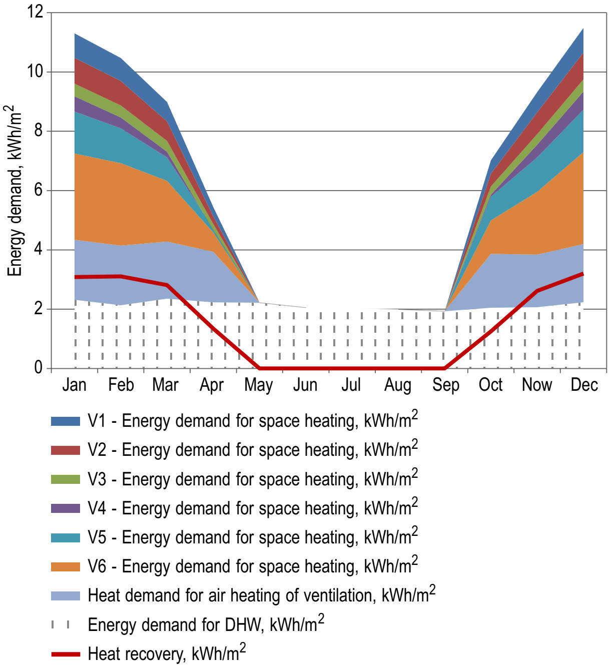

Fig. 3. The energy demand of the low energy house for space heating, ventilation and domestic hot water

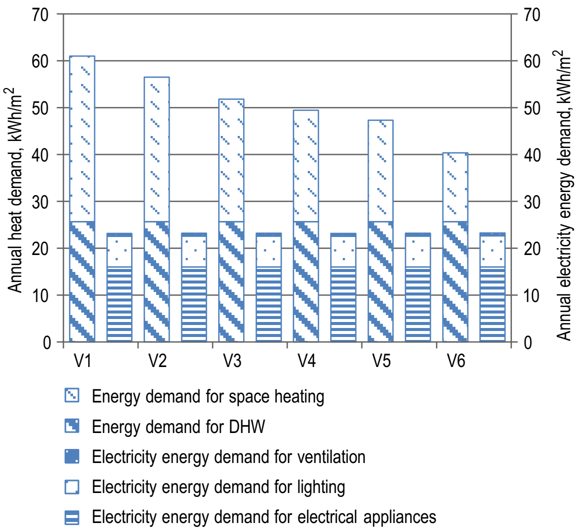

Fig. 4. The energy balance of the low energy house

the electricity demand for ventilation, lighting and electrical appliances is the same in all variants. The energy demand for space heating has the greatest impact on the total energy demand in the energy balance of the building.

2.2. Simulation of combinations of technologies of building energy supply system

Combinations of BESS technologies were set after the energy simulation of different building construction variants. In this study, 15 combinations of BESS technologies were analysed. The combinations from D1 to D15 consist of different types of generators (boilers, heat pumps) and the integrated technologies of renewable energy sources (solar collectors and solar cells). All combinations were simulated separately for every variant (from V1 to V6) of the building constructions, using simulation tool Polysun. The results of simulations and systematic energy analysis present the seasonal energy efficiencies of energy generation-transformation (ε_{gen}), storage (ε_s), distribution and emission ($\varepsilon_{e,d}$) subsystems, numerical values of which depend on the technical perfection of subsystems and the variation of climatic conditions over the year (Table 4). The analysis of results showed that the system performance factor (SPF) influences the formation of optimal BESS combination. SPF is expressed by the ratio of primary energy demand and building energy demand for space heating, ventilation and domestic hot water. Considering the energy efficiency, the best BESS combinations are with the integrated technologies of renewable energy sources (combinations from D1 to D6).

2.3. Constraints of renewable energy sources

This study focused on solar energy technologies (solar cells and solar collectors). These technologies were integrated into BESS combinations. The assumption was made that renewable energy produced on-site is not exported to the external grid. The main constraints of the integration of renewable energy sources into the building energy supply system originate due to the energy conversion process in technologies. Therefore, the main limitations for solar energy systems are set into the presented assessment model. In order to determine these limitations, the simulations of systems and sensitivity analysis were performed (Džiugaitė-Tumėnienė, Jankauskas 2013). The results showed that the option of 7.2 m^2 flat plate solar collectors (tilted 45°) with the 0.5 m^3 storage tank is the optimal decision, when the energy demand for DHW is lower than 372 kWh/per month. In this case, the total annual solar energy to the system is 21.4 kWh/m^2a (3281 kWh/a). Therefore, the total annual solar fraction of solar energy to the system is about 31%. The corresponding annual solar fraction for the DHW coverage is about 68.5%. The remaining auxiliary energy demand, covered by heat generator (boiler or heat pump), is 48.3 kWh/m^2a.

Table 4. Seasonal energy efficiency coefficients of generation, storage, distribution and emission subsystems of BESS of V1

Combination	The size of technology	$\varepsilon_{e,d}$	ε_s	ε_{gen}	ε_{SC}	ε_{PV}
D1	WB (11.2 kW, 500 l) + v.s.(190 m^3/h)	0.963	0.920	0.655	–	–
D2	WB (11.7 kW, 500 l) + v.s.(190 m^3/h) + SC (7.2 m^2)	0.964	0.930	0.624	0.372	–
D3	WB (11.7 kW, 500 l) + v.s.(190 m^3/h) + SC (7.2 m^2) + PV (200 W_p)	0.964	0.930	0.624	0.372	0.130
D4	PB (9.3 kW, 500 l) + v.s.(190 m^3/h)	0.962	0.920	0.791	–	–
D5	PB (10.1 kW, 500 l) + v.s.(190 m^3/h) + SC (7.2 m^2)	0.963	0.930	0.727	0.368	–
D6	PB (10.1 kW, 500 l) + v.s.(190 m^3/h) + SC (7.2 m^2) + PV (200 W_p)	0.963	0.930	0.727	0.368	0.130
D7	GB (7.7 kW, 300 l) + v.s.(190 m^3/h)	0.962	0.930	0.948	–	–
D8	GB (8.2 kW, 500 l) + v.s.(190 m^3/h) + SC (7.2 m^2)	0.962	0.920	0.896	0.361	–
D9	GB (8.2 kW, 500 l) + v.s.(190 m^3/h) + SC (7.2 m^2) + PV (200 W_p)	0.962	0.920	0.896	0.361	0.130
D10	$HP_{air–water}$ (7.3 kW, 300 l) + v.s.(190 m^3/h)	0.963	0.940	2.15	–	–
D11	$HP_{air–water}$ (7.3 kW, 500 l) + v.s.(190 m^3/h) + SC (7.2 m^2)	0.964	0.940	2.05	0.373	–
D12	$HP_{air–water}$ (7.3 kW, 500 l) + v.s.(190 m^3/h)+ SC (7.2 m^2) + PV (200 W_p)	0.964	0.940	2.05	0.373	0.130
D13	$HP_{brine–water}$ (7.3 kW, 300 l) + v.s.(190 m^3/h)	0.962	0.940	3.21	–	–
D14	$HP_{brine–water}$ (7.3 kW, 500 l) + v.s.(190 m^3/h)+ SC (7.2 m^2)	0.970	0.940	3.42	0.386	–
D15	$HP_{brine–water}$ (7.3 kW, 500 l) + v.s.(190 m^3/h)+ SC (7.2 m^2) + PV (200 W_p)	0.970	0.940	3.42	0.386	0.130

Solar cells of 200 W_p installed power are integrated into the combinations of D3, D6, D9, D12, D15. The polycrystalline solar cells of 1 m^2 are provided, which cover the annual electricity demand (34.4 kWh/a), required for the operation of circulation pump in the solar collector system. Therefore, the main technical constrains of solar energy technologies are: the solar collectors produce 3281 kWh/a of heat, solar cells – 34.4 kWh/a of electricity.

3. Results

Considering each criteria (energy, ecological, economic, comfort and system functionality) separately, the different optimal configuration of BESS is obtained. The combination of D6 is optimal according to energy and ecological criteria. However, in pursuance of economic efficiency, the optimal combination is D1. When functionality criterion is important, the combination of D7 has to be selected. Therefore, the assessment results of combinations show that the mismatch between indicator values (primary energy demand, amount of CO_2 emissions, global cost, comfort, functionality) complicates the final decision making. The multicriteria decision making method WASPAS is used for the integrated assessment of BESS technology combinations. The results are presented in Figure 5, which demonstrate that the optimal combination is D1, when the main heat generator is a wood boiler and electricity is supplied by the national electricity grid.

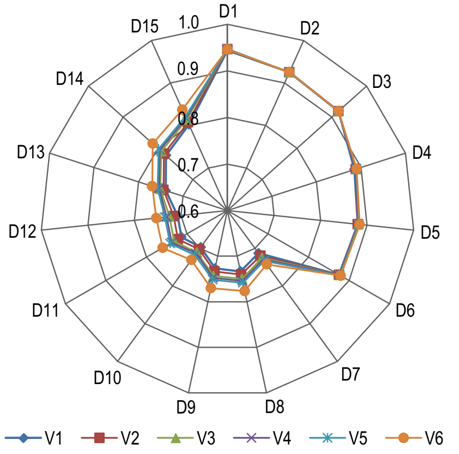

Fig. 5. Optimal combination of technologies of a building energy supply system

Comparing variants of building constructions, the highest optimal value is obtained in case of V4 (Table 5). As can be seen from Table 5, the additional insulation for V6 variant of building construction determines the decrease of primary energy by 5.5%, CO_2 emission by 2.4%, global cost by 9%, comparing to the results of V1 variant.

In case of V6, the heat transfer coefficient of walls is increased by 67%, roof – 54%, ground – 60%, and the heat transfer coefficient of windows is decreased by 49%. Therefore, the research shows, that the selection of optimal combination of BESS technologies has the greatest impact on the final energy performance of the building.

Conclusions

1. The presented multicriteria assessment model of the building energy supply system allowed determining the optimal combination of the technologies of building energy supply system (BESS) considering energy efficiency, environmental impact, economic rationality, comfort and functionality criteria.
2. The results showed that the selection of optimal combination of BESS technologies has the greatest impact on the final energy performance of the building, because the additional insulation of building constructions, when the heat transfer coefficient of walls is increased by 67%, roof – 54%, floor – 60% and the heat transfer coefficient of windows is decreased by 49%, gives the reduction of final energy only by 5.5%, CO_2 emission by 2.4% and the global cost by 9%.

Table 5. The optimal values of variants of building constructions

	PE, kWh/m^2	CO_2, kg_{CO2}/m^2	GC, LTL/m^2	Cmf, %	Fnc, %	Opt. combination	Optimal value
V1	83.3	15.1	505	49.3	67	D1	0.94386
V2	81.9	15.0	494	54.9	67	D1	0.94635
V3	80.7	14.8	482	55.2	67	D1	0.94704
V4	80.1	14.8	477	58.0	67	D1	0.94733
V5	79.8	14.8	473	55.2	67	D1	0.94727
V6	78.7	14.7	460	56.3	67	D1	0.94614

3. Considering the implementation of the requirements for the low energy and passive houses in Lithuania and other cold climate countries, the optimal solution is:
   - heat transfer coefficients for: walls – 0.11 W/m^{2}K, roof – 0.09 W/m^{2}K, floor – 0.12 W/m^{2}K, windows – 0.80 W/m^{2}K;
   - building energy supply system – wood boiler and the electricity from the national electricity grid. The optimal value can be achieved, when primary energy demand is 80 kWh$_{PE}$/m^2, the amount of CO$_2$ emissions is 14.8 kg$_{CO2}$/m^2 and the share of renewable energy sources is 58%.

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MAŽAENERGIO PASTATO APRŪPINIMO ENERGIJA DAUGIATIKSLIO VERTINIMO MODELIS

R. Džiugaitė-Tumėnienė, V. Lapinskienė

Santrauka. Mažaenergio pastato efektyvaus aprūpinimo energija tyrimai yra svarbūs įgyvendinant pastatų energinio naudingumo tikslus, siekiant padidinti energijos vartojimo efektyvumą ir atsinaujinančiųjų išteklių energijos dalį bendrajame suvartojamos energijos balanse, taip pat sumažinti šiltnamio efektą sukeliančių dujų emisijas. Atliekant tyrimus taikomi integruoto vertinimo metodai, siejantys pastato energinį modeliavimą ir optimizavimą, nustatantys racionalius sprendinius tik pagal kiekybinius kriterijus (energinius, techninius, ekologinius ir ekonominius). Tokio požiūrio nepakanka siekiant įdiegti racionalią pastato aprūpinimo energija sistemą kiekybinių ir kokybinių kriterijų atžvilgiu.

Straipsnyje pateikiamas mažaenergio pastato aprūpinimo energija daugiatikslio vertinimo modelis, kuriuo remiantis iš pasirinktų šešių pastato konstrukcijų variantų ir jiems numatytų 15 PAES technologijų derinių nustatytas racionalus PAES technologijų derinys, vertinimo kriterijais imant energinį efektyvumą, poveikį aplinkai, ekonominį racionalumą, sukuriamą komfortą ir sistemos funkcionalumą. Tyrimo rezultatai parodė, kad, Lietuvoje ir panašaus klimato šalyse įgyvendinant mažaenergiams ir pasyviems vienbučiams namams keliamus reikalavimus, racionalus sprendinys yra pastato atitvaros, atitinkančios A+ energinio naudingumo klasės reikalavimus, su PAES deriniu, kurį sudaro biologinio kuro (malkų) katilas ir iš nacionalinių elektros tinklų tiekiama elektros energija.

Reikšminiai žodžiai: mažaenergis pastatas, pastato aprūpinimo energija sistema, *DesignBuilder*, *Polysun*, WASPAS.

Rasa DŽIUGAITĖ-TUMĖNIENĖ. PhD student of Energetics and Thermal Engineering (since 2009), MSc in Energetics (2006), BA in Energetics (2004), Vilnius Gediminas Technical University. Publications: author of 10 research papers. Research interests: energy efficiency in buildings, integration of renewable energy sources into the energy supply systems, energy simulations.

Vilūnė LAPINSKIENĖ. PhD student of Civil Engineering (since 2012), MSc in Energetics (2010), BA in Energetics (2008), Vilnius Gediminas Technical University. Publications: author of 10 research papers. Research interests: building information modelling, integrated building design, energy simulation, energy efficiency in buildings.