Scientific Review – Engineering and Environmental Sciences (2018), 27 (4), 567–578
Sci. Rev. Eng. Env. Sci. (2018), 27 (4)
Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska (2018), 27 (4), 567–578
Prz. Nauk. Inż. Kszt. Środ. (2018), 27 (4)
http://iks.pn.sggw.pl
DOI 10.22630/PNIKS.2018.27.4.52

Marcin ZYGMUNT, Marcin PICZULSKI

Faculty of Civil Engineering, Architecture and Environmental Engineering, Lodz University of Technology

Economic, environmental and social aspects of buildings' refurbishment – a case study

Key words: sustainable development, life cycle cost, life cycle assessment, energy efficiency, renewable energy, energy demand simulation

Introduction

The concept of sustainable development (PN-EN 15643-1:2011) is a very broad definition, on many fields such as construction or transport. Today's requirements for new or modernized buildings and growing public awareness about sustainable development aspect are leading to the application of pro-ecological solutions. The subject of the construction project is increasingly not only building durability, thermal quality of building partitions and the installations used, but also the impact of the construction process during the whole life cycle of this building, the use of renewable energy and the quality of the indoor environment. The main assumption of the idea of sustainable development (Fig. 1) is the ability to find a common part between environmental (PN-EN 15643-2:2011), economic (PN-EN 15643-4:2012) and social (PN-EN 15643-3:2012) aspects.

The economic pillar is a detailed cost analysis of modernization – life cycle cost (LCC) analysis (Commission Delegated Regulation (EU) 244/2012)

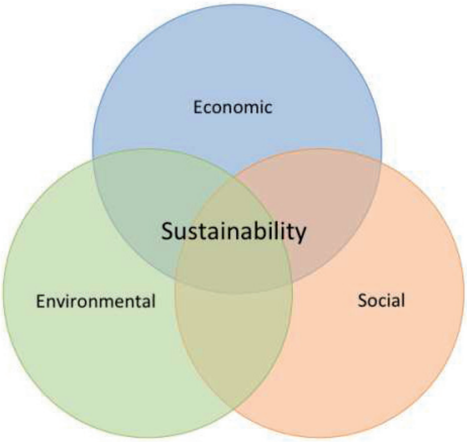

FIGURE 1. Sustainable development pillars schema (PN-EN 15643-1:2011)

taking into account the whole process of existence of a given undertaking – starting from obtaining materials, product production, its transport, use, exploitation, ending with disassembly together with possibility of recycling. The social pillar assumes all factors affecting the internal environment, in particular thermal and acoustic comfort, indoor air quality or related to the feeling of safety (PN--EN ISO 16309:2014). The environmental pillar is an assessment of the investment's impact on the environment, made using the life cycle assessment (LCA) analysis (PN-EN 15804:2012). The environmental pillar is based on rational water management, control and reduction of energy demand, renewable energy use as well as correct material management, which assumes recycling or re-use of this material (PN-EN 15804:2012, PN--EN 15978:2012). One of the most important aspects of the proper functioning of individual buildings as well as large enterprises is energy management. The environmental pillar assumes an assessment to the energy consumption of a building with a specification of primary non-renewable and renewable energy. The assessment of the energy demand of the building allows to determine the energy quality of the analyzed object, in particular the effectiveness of the material, construction and utility solutions. Among of proper energy management is the reduction of energy consumption, obtained through appropriate control of the installations or construction modernizations, but also peak load. In accordance with today's requirements, buildings are increasingly using energy obtained from renewable sources, among which solar and wind energy are the leaders. The unpredictability and irregularity of obtaining energy from renewable sources results in intense development of the electricity storage technologies (Komarnicki, 2016). The combination of proper management of energy consumption, the use of renewable sources and the energy storage use leads to the development of distributed energy and the emergence of the smart grid areas.

This article presents selected analyzes consistent with the idea of sustainable development, for energy cluster and office building. The results of the analysis for energy cluster area were presented first. The analysis contains a description of the cluster itself, presentations of the calculation tool and LCC and LCA analysis results for the indicated modernization. Then a detailed analysis of the real office building was presented. The analysis was based on the actual energy consumption data of the building. The research is based on advanced computer simulations carried out using DesignBuilder software (DesignBuilder EnergyPlus Simulation Documentation), which is an overlay for the EnergyPlus program (EnergyPlus Engineering Reference). All simulations were performed for an hourly calculation step. The presented results concern the distribution of energy demand and verification of thermal comfort. At the end of the article, the authors drew conclusions from the presented analyzes.

Analysis of the energy cluster

Analysis of the energy cluster was based on the results obtained from the spreadsheet. The structure of the created tool is extensive, it consists of the module: energy, environmental and cost. The developed spreadsheet allows making an analysis of the energy cluster created from the database of building types available in the tool. The structure of the tool assumes the modeling of an energy cluster consisting of buildings of various types. Buildings are dependent on the construction year, their purpose and energy performance (National Energy Conservation Agency, 2012). Analysis of the modeled cluster assumes energy consumption for heating, hot utility water and facility use (lighting, household appliances, etc.). Then, energy and modernization analysis (based on the methodology of the energy performance of the building) and environmental – raw materials (performed based on the EPD declaration for individual materials or devices used, as well as emission factors for used energy carriers) are possible for a given energy cluster. Figure 2 presents a typical step-by-step procedure (methodology) for the energy and environmental analysis of an energy cluster.

Within the framework of this article, an energy cluster consisting of 1,507 buildings of various types (Table 1) located in the Łódź region was modeled.

The annual energy demand depending on the carrier and building type is shown in Table 2. For the analyzed cluster it was assumed that:

– for single-family houses, heating is performed in 95% using coal, and in 5% using biomass; preparation of domestic hot water depending on the type of the building;
– for multi-family and public buildings heating is carried out through natural gas, and the preparation of hot utility water thanks to electricity.

These assumptions were selected based on the GUS (2017). They refer to the conditions found in typical households in the countryside.

The energy demand for heating was computed using the monthly balance method, on the other hand, the energy demand for domestic hot water preparation was calculated based on the usable floor area of buildings. Both methods were taken from (Regulation of the Minister of Infrastructure and Development of 27 February 2015).

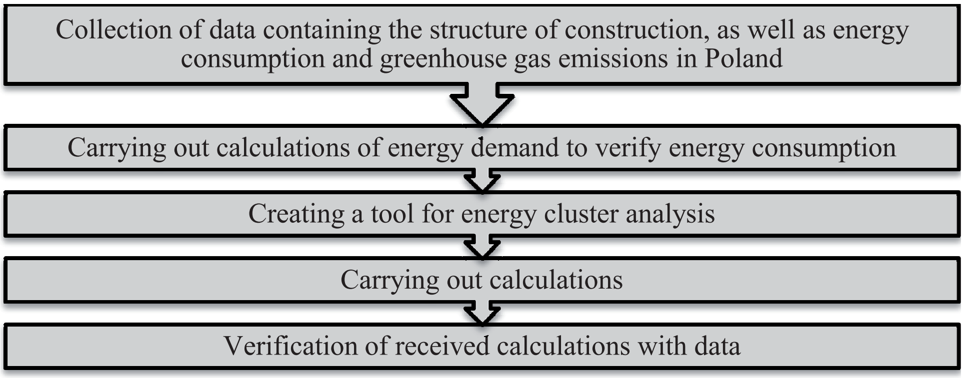

FIGURE 2. The scheme of an energy cluster analysis (own studies)

TABLE 1. Structure and characteristics of building in the base variant for the analyzed energy cluster (own studies)

Type of building	Construction period	Number of buildings	Heating area [m^2]	*EP* [kWh·year^{-1}·m^2]
SFH*	before 1945	338	72.00	477.65
SFH*	1946–1966	435	98.20	422.21
SFH*	1967–1985	195	130.00	330.15
SFH*	1986–1992	209	136.00	249.44
SFH*	1993–2002	173	160.00	164.58
SFH*	2003–2008	83	172.00	110.60
SFH*	after 2008	68	178.00	119.30
MFH**	1990	2	292.50	357.88
Communal	1960	3	668.20	299.46
School	1970	1	828.00	504.75

* SFH – single-family house.
** MFH – multi-family house.

TABLE 2. Energy consumption of buildings in the base variant for the analyzed energy cluster (own studies)

Type of building	Construction period	Annual energy demand for all buildings of a given type			
		bituminous coal [GJ·year^{-1}]	natural gas [GJ·year^{-1}]	biomass [GJ·year^{-1}]	electrical energy [GJ·year^{-1}]
SFH	before 1945	30 878.02	0.00	1 534.31	4 911.35
SFH	1946–1966	49 673.60	0.00	2 646.05	7 371.17
SFH	1967–1985	23 181.06	0.00	1 253.03	3 875.80
SFH	1986–1992	21 092.90	0.00	1 059.94	4 269.63
SFH	1993–2002	17 601.60	0.00	965.94	3 009.39
SFH	2003–2008	5 633.12	0.00	279.16	1 535.60
SFH	after 2008	4 764.48	0.00	202.81	1 295.69
MFH	1990	0.00	512.85	0.00	117.07
Communal	1960	0.00	1 871.50	0.00	107.92
School	1970	0.00	1 298.71	0.00	186.29

Values of emission of harmful substances into the environment of the analyzed energy cluster were calculated on grounds of energy consumption and emission factors and presented in Table 3.

This article presents the results obtained for the assumption of bringing objects forming part of the energy cluster to the *EP* index value standards required from 1 January 2021 (Regulation of the Minister of Infrastructure of 12 April 2002). The variant assumes insulation of external partitions, replacement of window frames, modernization or replacement of the heating system and the possible use of renewable energy (for all buildings it was assumed that the preparation of hot utility water will be supported by solar collectors). Table 4 presents data on modernized buildings in the energy cluster.

of non-renewable energy consumption, CO_2 emission as well as LCC analysis for the 30-year period. Table 7 presents the total results of non-renewable energy consumption in 30 years, production of CO_2 for the atmosphere over 30 years, as well as the results of LCA analysis for the modernization of buildings (taking into account only the construction materials used) and the total cost of the energy cluster in the 30-year period.

TABLE 3. Annual emission in the base variant for the analyzed energy cluster (own studies)

Issue of compounds [kg]						
CO_2	SO_x	NO_x	CO	benzo- -pyrene	PM10	PM2.5
13 115 479	108 203	15 379	317 398	95	66 412	64 562

TABLE 4. Structure and characteristics of buildings in the variant after modernization for the analyzed energy cluster (own studies)

Type of building	Construction period	Number of buildings	Heating area [m^2]	*EP* [$kWh \cdot year^{-1} \cdot m^{-2}$]
SFH	before 1945	338	72.00	42.07
SFH	1946–1966	435	98.20	34.40
SFH	1967–1985	195	130.00	67.13
SFH	1986–1992	209	136.00	71.32
SFH	1993–2002	173	160.00	71.26
SFH	2003–2008	83	172.00	75.47
SFH	after 2008	68	178.00	26.43
MFH	1990	2	292.50	42.06
Communal	1960	3	668.20	18.63
School	1970	1	828.00	32.53

The annual energy demand for the energy cluster modernization variant is shown in Table 5.

Values of emission of harmful substances into the environment of the analyzed variant are presented in Table 6.

The analysis of modernization of the energy cluster includes a comparison

Analysis of advanced computer simulations use

Currently, as a standard methodology for determining the energy performance of a building is monthly balance method (quasi-fixed), which based on monthly

TABLE 5. Energy consumption of buildings in the variant after modernization for the analyzed energy cluster (own studies)

Type of building	Construction period	Annual energy demand for all buildings of a given type			
		bituminous coal [GJ·year^{-1}]	natural gas [GJ·year^{-1}]	biomass [GJ·year^{-1}]	electrical energy [GJ·year^{-1}]
SFH	before 1945	0.00	0.00	5 987.65	3 326.04
SFH	1946–1966	0.00	0.00	10 359.48	5 420.76
SFH	1967–1985	5 049.14	0.00	0.00	3 050.37
SFH	1986–1992	6 215.89	0.00	0.00	3 394.82
SFH	1993–2002	7 109.26	0.00	0.00	2 769.22
SFH	2003–2008	3 422.42	0.00	0.00	1 428.23
SFH	after 2008	0.00	0.00	2 991.18	1 210.93
MFH	1990	0.00	0.00	209.05	74.08
Communal	1960	0.00	0.00	583.60	90.09
School	1970	0.00	0.00	365.89	171.08

TABLE 6. Annual emission in the variant after modernization for the analyzed energy cluster (own studies)

Issue of compounds [kg]						
CO_2	SO_x	NO_x	CO	benzo-pyrene	PM10	PM2.5
3 360 136	15 569	3 435	77 543	14	3 760	3 441

TABLE 7. Total results for the energy cluster for the analyzed energy cluster (own studies)

Non-renewable energy consumption [TJ]			Issue of CO_2 [Gg]			Total cost over a 30-year period [PLN]	
base variant	variant after modernization	materials used (LCA)	base variant	variant after modernization	materials used (LCA)	base variant	variant after modernization
5 487.94	10.06	109.37	393.46	100.80	6.52	411 696 491.00	410 188 019.00

averages of the external climate data, heat gains and losses and HVAC installation efficiency (Regulation of the Minister of Infrastructure and Development of 27 February 2015). The calculations made according to mentioned methodology are used to estimate the energy consumption of the building. With use of the methodology it is not possible to take into account the dynamics of the building or variable operation of the installation.

Advanced energy simulations (performed with at least an hour computational step) fully reflect the dynamics of climate conditions and the response of the installation to the thermal load of the

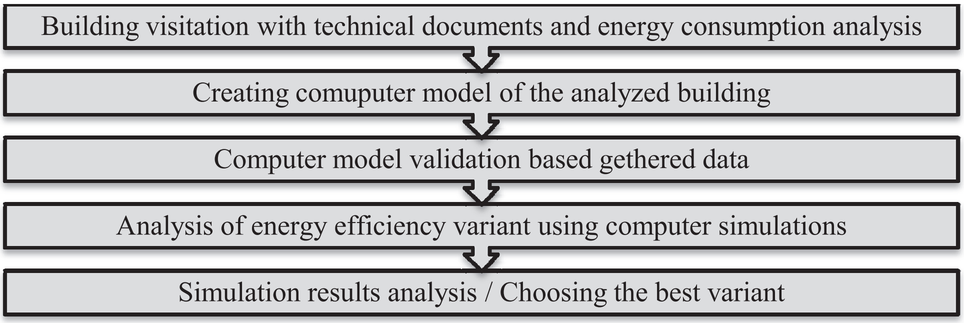

FIGURE 3. The scheme of advanced energy simulation procedure (own studies)

FIGURE 4. Photo of the analyzed object (own studies)

building (Royapoor & Roskilly, 2015). After obtaining certainty that created computer model fully reflects the real behavior of the analyzed building, it is possible to evaluate the energy efficiency of the object. At Figure 3 shows typical step by step procedure (methodology) of performing advanced energy simulation analysis.

The analyzed object is a real construction, located in Gdańsk. It is an office building, built of two towers, 10 and 12 storeys each (Fig. 4). The building was commissioned in December 2013. The analyzed facility is part of a complex of office buildings. The building is characterized by a glass facade of both towers.

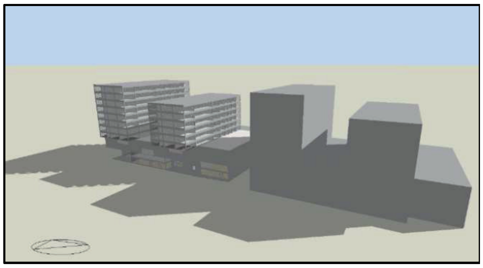

FIGURE 5. Computer visualization of the analyzed object along with the nearest neighborhood (own studies)

The computer model of the analyzed building was made using DesignBuilder software, which is an overlay for the EnergyPlus software – the leading program for advanced energy simulation in the world. The building model (Fig. 5) was created based on the design documentation of the analyzed building. Analyzes took into account shading from neighboring buildings – a direct neighborhood of the analyzed object was added in the computer model.

Energy simulations were made based on real energy consumption data received from the analyzed building manager and building technical office. The data contained detailed information about electricity consumption for the period 18–31.07.2016 with the division into

TABLE 8. Comparison of energy consumption during computer model validation simulation (own studies)

Loads	Real use [kWh]	Simulation [kWh]	Difference	
			kWh	%
Chillers	6 658.20	6 624.02	34.18	0.51
Lighting	1 588.80	1 630.43	–41.63	2.62
Fans	11 868.28	10 927.81	940.47	7.92
Pump	831.70	852.68	–20.98	2.52
Electric equipment	7 919.22	7 868.77	50.45	0.64
Sum	28 866.20	27 903.71	962.49	3.33

individual receipts and the work schedule. In addition, among the data, there were hourly external climate readings. Other meteorological data were adopted from the typical meteorological year for Gdańsk. The data complemented the diagrams and working hours of individual devices as well as the object itself.

First, the computer model of the building was calibrated to verify compliance with the actual energy consumption (Table 8). By comparing each load in Table 8 we can see, that the computer model of the analyzed building correctly reflects the structure and dynamics of energy consumption (the obtained energy consumption differences are acceptable). Simulation made using created model can be used for a detail analysis of modernization solutions as well as for assessing the quality of the internal environment.

This article presents the results obtained for the following modernizations:

- Variant 1 – simulation assuming the replacement of the glass facade (real glazing by SunGuard Glass company); facade parameters are summarized in Table 9.
- Variant 2 – simulation assuming a change of distributing chill and heat equipment in office rooms; the variant assumes the conversion of fan coils into chilled beams.
- Variant 3 – a combination of Variants 1 and 2.

Figure 6 presents the distribution of electricity demand for the analyzed variants, compared to the real state of the analyzed object. In Figure 6, we can see, that Variant 1 resulted in lowering electricity peak demand compering to current use. Additionally, Table 10 shows the energy consumption divided into individual loads and total electricity consumption for the analyzed variants compering to current use. The analysis shows that:

- Variant 1 effectively reduces the cooling power demand, thereby lowering peak demand values; there has been a clear (by 9.86%) reduction in total electricity consumption.
- Variant 2 generates lower total electricity consumption (by 5.78%), however we observe a higher cooling power demand – this leads to increase peak demand compering to current use.

TABLE 9. List of analyzed glass (own studies)

Factor	Present glass	Analyzed glass
Heat transfer coefficient, U [W·m^{-2}·K^{-1}]	1.00	1.00
Light transmission, L_T [-]	0.61	0.50
Solar heat gain coefficient, *SHGC* [-]	0.34	0.23

– Variant 3 is characterized by the biggest reduction in total energy consumption (by 11.79%); peak demand values are slightly lower than in Variant 2, but still higher than in current use.

All proposed modernization options should be checked in order to ensure appropriate internal environmental conditions (Yang, Yan & Lam, 2014). Even the most beneficial modernization reducing energy consumption or lowering the

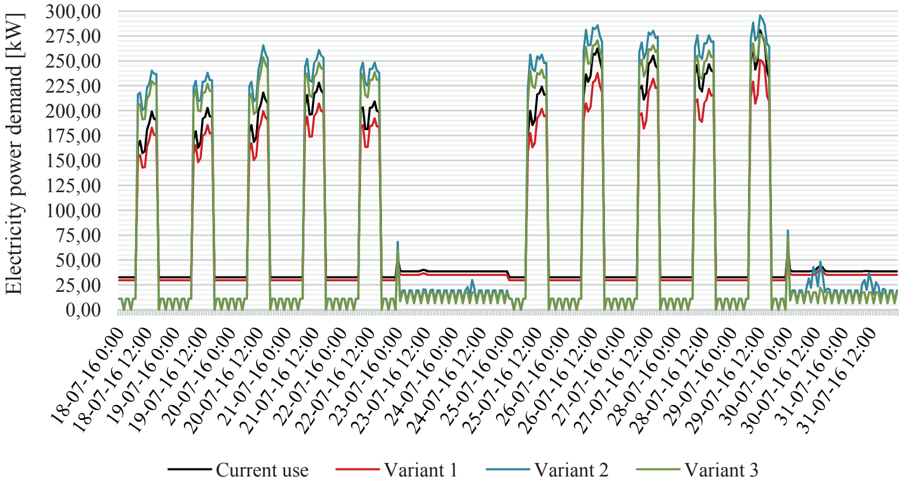

FIGURE 6. Total electricity power demand for analyzed variants for 18–31.07.2016 period (own studies)

TABLE 10. Electricity energy consumption for analyzed variants (own studies)

Loads		Current use [kWh]	Variant 1 [kWh]	Variant 2 [kWh]	Variant 3 [kWh]
Chillers		6 624.02	4 900.80	12 134.52	10 626.48
Lighting		1 630.43	1 643.94	1 630.43	1 643.94
Fans		10 927.81	9 993.90	3 799.79	3 799.97
Pump		852.68	744.85	856.01	674.86
Electric equipment		7 868.77	7 868.77	7 868.77	7 868.77
Sum		27 903.71	25 152.26	26 289.52	24 614.02
Reduction	kWh		2 751.45	1 614.19	3 289.69
	%		9.86	5.78	11.79

peak demand in not acceptable if it does not ensure the proper quality of the internal environment conditions. Simulations were checked for thermal comfort (PN-EN ISO 7730:2006) using the PMV (predicted mean vote) index. PMV index informs about the feeling of people in the given internal environment. The value of the PMV index is influenced by internal environment factors (such as temperature or relative humidity of the internal air) and parameters describing people staying in given environment (activity, thermal insulation of clothing). The simulations assume following parameters:

- indoor air temperature: 24°C (while work hours),
- activity: office work – 1.20 met,
- thermal insulation of clothing: 0.70 clo.

The distribution of the PMV index for the analyzed variants presents Figure 7. For building's working hours (the period of employees staying inside the analyzed building), the value of PMV index ranges from –0.65 to 0.88. The value of the PMV index are correct compering with recommended values (PN-EN 15251:2012).

Conclusions

The energy cluster analyzed can be an example of a typical Polish commune. Saving in the aspect of non-renewable primary energy consumption, including LCA analysis of materials used during the modernization of buildings, is nearly 98%. In economic terms, the chosen option of modernizing the energy cluster may be more optimal. For some types of buildings, the way of meeting the value of the *EP* indicator adopted in the analysis is unprofitable. One should look for a solution that at the same time generates savings on the consumption of non-renewable primary energy and CO_2 produced in the atmosphere and is more economically viable. Such a solution can

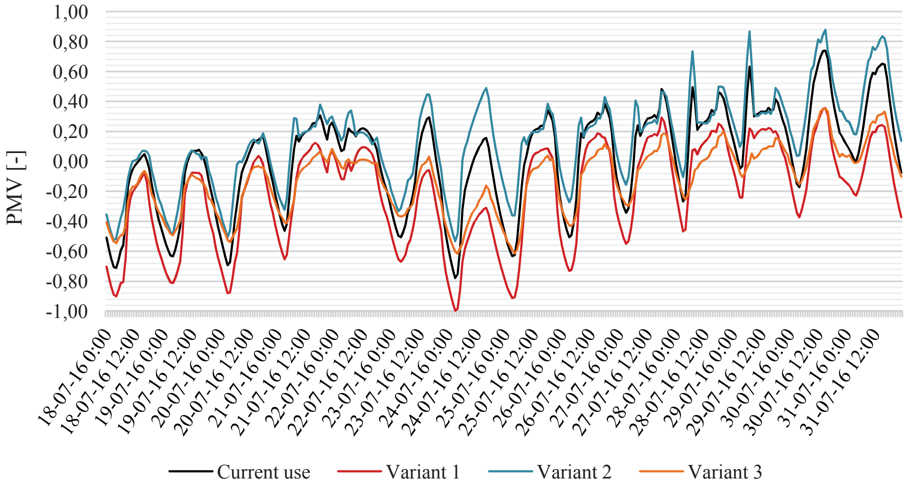

FIGURE 7. Thermal comfort distribution for analyzed variants for 18–31.07.2016 period using PMV index (own studies)

be the use of renewable energy, in particular, the use of heat pumps in combination with PV installations.

The analysis of the office building using computer simulations with an hourly computational step shows potential of their use. The results obtained by this method reflect the dynamics of the installation as well as the building itself. The results include total energy consumption as well as the temporary peak power demand. One of the results that we can obtain by using computer simulations is the analysis of thermal comfort of the internal environment. Such detail results cannot be obtained using monthly balance method. In addition, advanced computer simulations allow to assess the cost of modernization for the analyzed building with high probability.

References

Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements]. OJ L 81 of 21.03.2012, pp. 18-36.

Główny Urząd Statystyczny – GUS (2017). *Zużycie energii w gospodarstwach domowych w 2015 r*. [Energy consumption in households in 2015]. [Energy consumption in households in 2015]. Warszawa: Dział Wydawnictw Statystycznych GUS.

Komarnicki, P. (2016). Energy storage systems: Power grid and energy market use cases. *Archives of Electronical Engineering*, *65*(3), 495-511. DOI 10.1515/aee-2016-0036

Narodowa Agencja Poszanowania Energii – NAPE (2011). *Podręcznik typologii budynków mieszkalnych z przykładami działań mających na celu zmniejszenie ich energochłonności w ramach projektu IEE TABULA*. Warszawa: NAPE.

PN-EN 15251:2012. Parametry wejściowe środowiska wewnętrznego dotyczące projektowania i oceny charakterystyki energetycznej budynków, obejmujące jakość powietrza wewnętrznego, środowisko cieplne, oświetlenie i akustykę [Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics].

PN-EN 15643-1:2011. Zrównoważoność obiektów budowlanych. Ocena zrównoważoności budynków. Część 1: Zasady ogólne środowiskowych [Sustainability of construction works. Assessment of buildings. General principles].

PN-EN 15643-2:2011. Zrównoważoność obiektów budowlanych. Ocena budynków. Część 2: Zasady oceny właściwości środowiskowych [Sustainability of construction works. Assessment of buildings. Framework for the assessment of environmental performance].

PN-EN 15643-3:2012. Zrównoważone obiekty budowlane. Ocena budynków. Część 3: Postanowienia dotyczące oceny socjalnych właściwości użytkowych [Sustainability of construction works. Assessment of buildings. Framework for the assessment of social performance].

PN-EN 15643-4:2012. Zrównoważone obiekty budowlane. Ocena budynków. Część 4: Postanowienia dotyczące oceny ekonomicznych właściwości użytkowych [Sustainability of construction works. Assessment of buildings. Framework for the assessment of economic performance].

PN-EN 15804:2012. Zrównoważoność obiektów budowlanych. Deklaracje środowiskowe wyrobów. Podstawowe zasady kategoryzacji wyrobów budowlanych [Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products].

PN-EN 15978:2012. Zrównoważone obiekty budowlane. Ocena środowiskowych właściwości użytkowych budynków. Metoda obliczania [Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method].

PN-EN ISO 16309:2014. Zrównoważone obiekty budowlane. Ocena socjalnych właściwości użytkowych budynków. Metodyka obliczania [Sustainability of construction works. Assessment of social performance of buildings. Calculation methodology].

PN-EN ISO 7730:2006. Ergonomia środowiska termicznego. Analityczne wyznaczanie i interpretacja komfortu termicznego z zastosowaniem obliczania wskaźników PMV i PPD oraz kryteriów miejscowego komfortu termicznego [Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria].

Royapoor, M. & Poskilly, T. (2015). Building model calibration using energy and environmental data. *Energy and Building Journal, 94*, 109-120.

Rozporządzenie Ministra Infrastruktury i Rozwoju z dnia 27 lutego 2015 r. w sprawie metodologii wyznaczania charakterystyki energetycznej budynku lub części budynku oraz świadectw charakterystyki energetycznej [Regulation of the Minister of Infrastructure and Development of 27 February 2015 on the methodology for determining the energy performance of a building or part of a building and energy performance certificates]. Journal of Laws 2015, item 376.

Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie [Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions, which should correspond to the buildings and their location]. Journal of Laws 2002 no 75, item 690.

Yang, L., Yan, H. & Lam, C.J. (2014). Thermal comfort and building energy consumption implications – A review. *Applied Energy Journal*, *115*, 164-173.

Summary

Economic, environmental and social aspects of buildings' refurbishment – a case study. The aim of the article is to presents the results of calculations regarding the: economic – based on the life cycle costing (LCC) approach, environmental – based on the life cycle assessment (LCA) approach and social aspects of modeled refurbishment of residential and non-residential stock of buildings. Particular emphasis was placed on the impact of energy efficiency of the modeled buildings on environmental aspects and the selection of renewable and non-renewable energy sources. The article presents an analysis of an area of energy cluster in terms of environmental aspects and a detailed analysis of an office building using advanced energy simulations. The calculations for energy cluster was made using Polish energy certificate methodology (monthly calculations) while analysis of an office building was performed using dynamic hourly simulations with use of Energy Plus software. Performed analysis results in reaching energy efficiency scenarios for both cases according to meeting sustain development idea.

Authors' address:
Marcin Zygmunt, Marcin Piczulski
Politechnika Łódzka
Wydział Budownictwa, Architektury i Inżynierii Środowiska
Katedra Fizyki Budowli i Materiałów Budowlanych
ul. Żurawia 12/42, 91-463 Łódz
Poland
e-mail: marcin.zygmunt@p.lodz.pl
marcin.piczulski@edu.p.lodz.pl